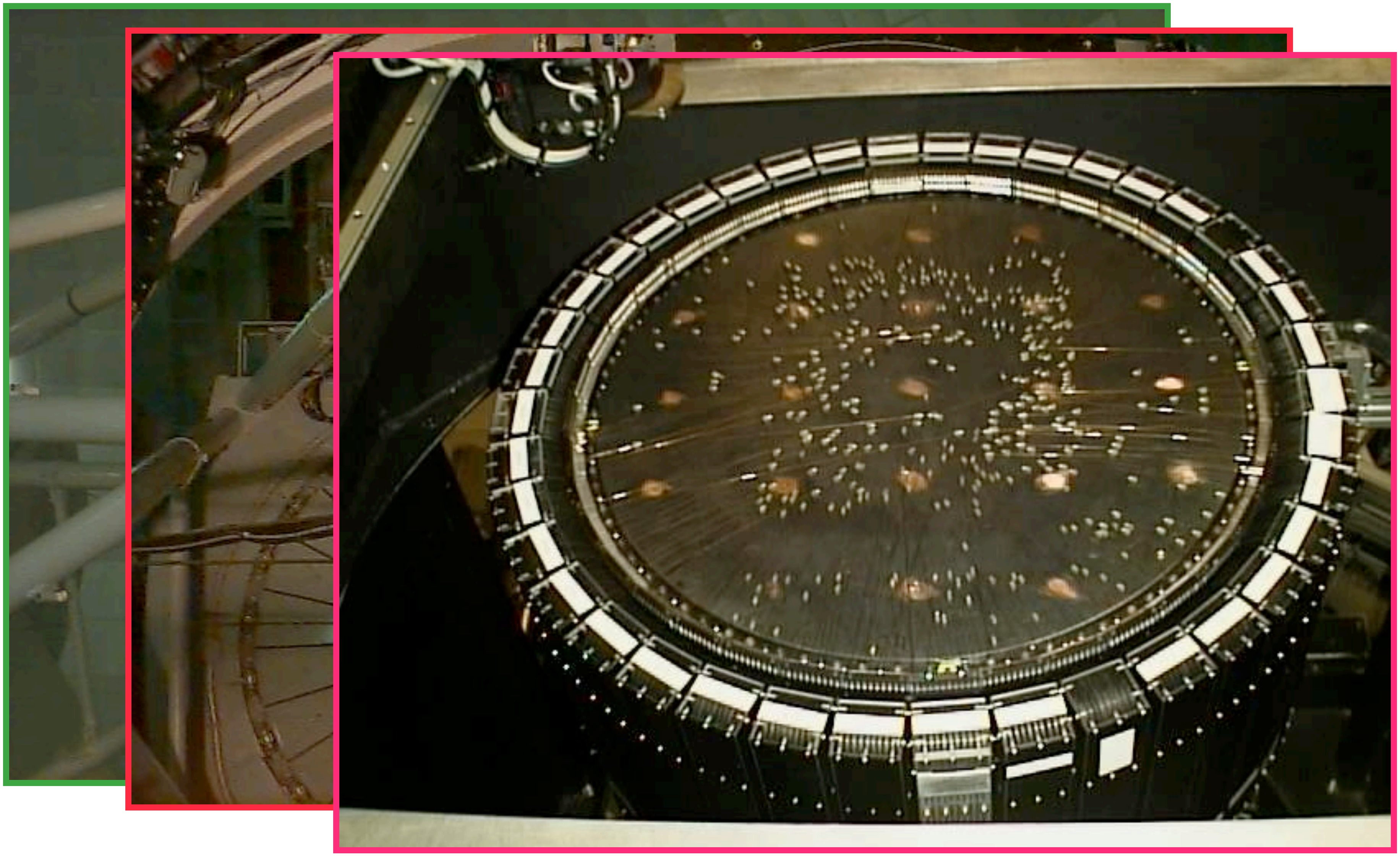
Gravitational Lensing:
Einstein's Unfinished Symphony

Richard Ellis (Caltech)

http://www.astro.caltech.edu/~iran1.pdf

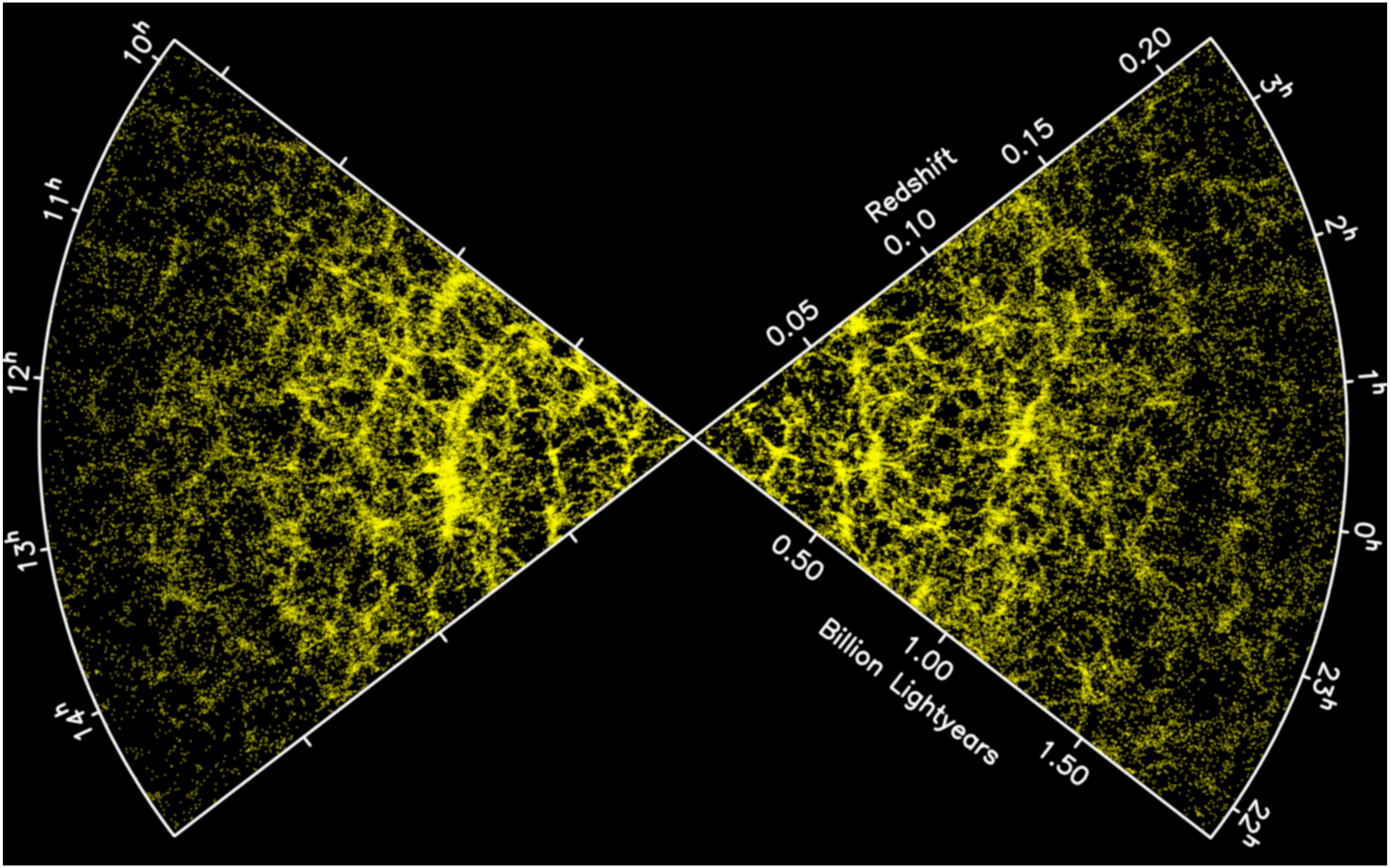
April 2011

Progress in Cosmology: I - Galaxy Surveys

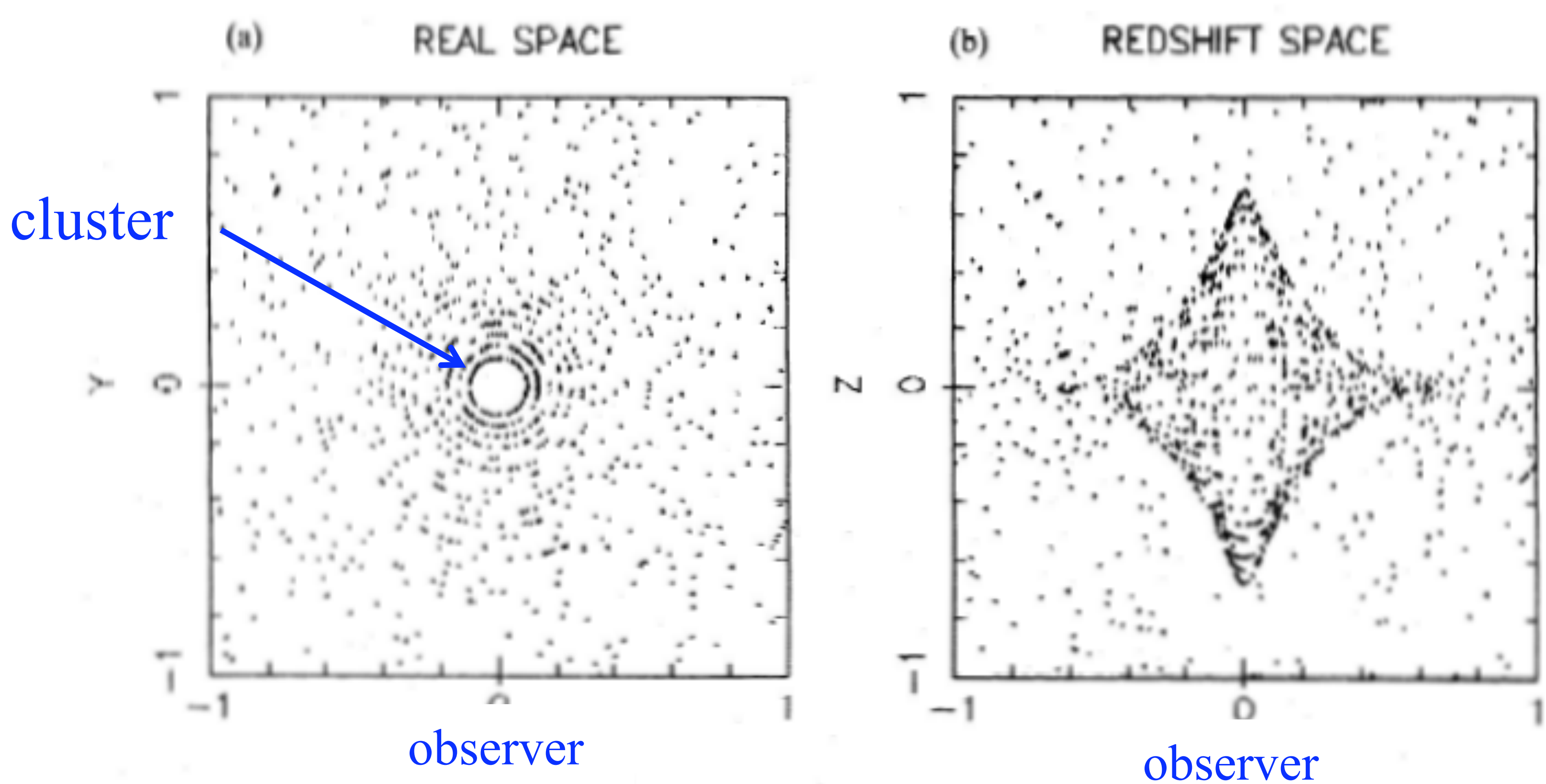


Australian Astronomical Observatory: 2 degree field facility

2dFGRS Galaxy Redshift Survey

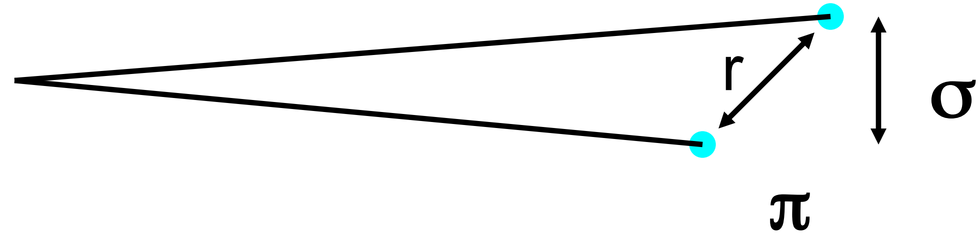


Galaxy distribution is distorted in redshift space



Peculiar velocities distort the distribution of galaxies in redshift space; this can provide a measure of the mass density of dark matter associated with galaxies on larger scales

2dF redshift-space distortions



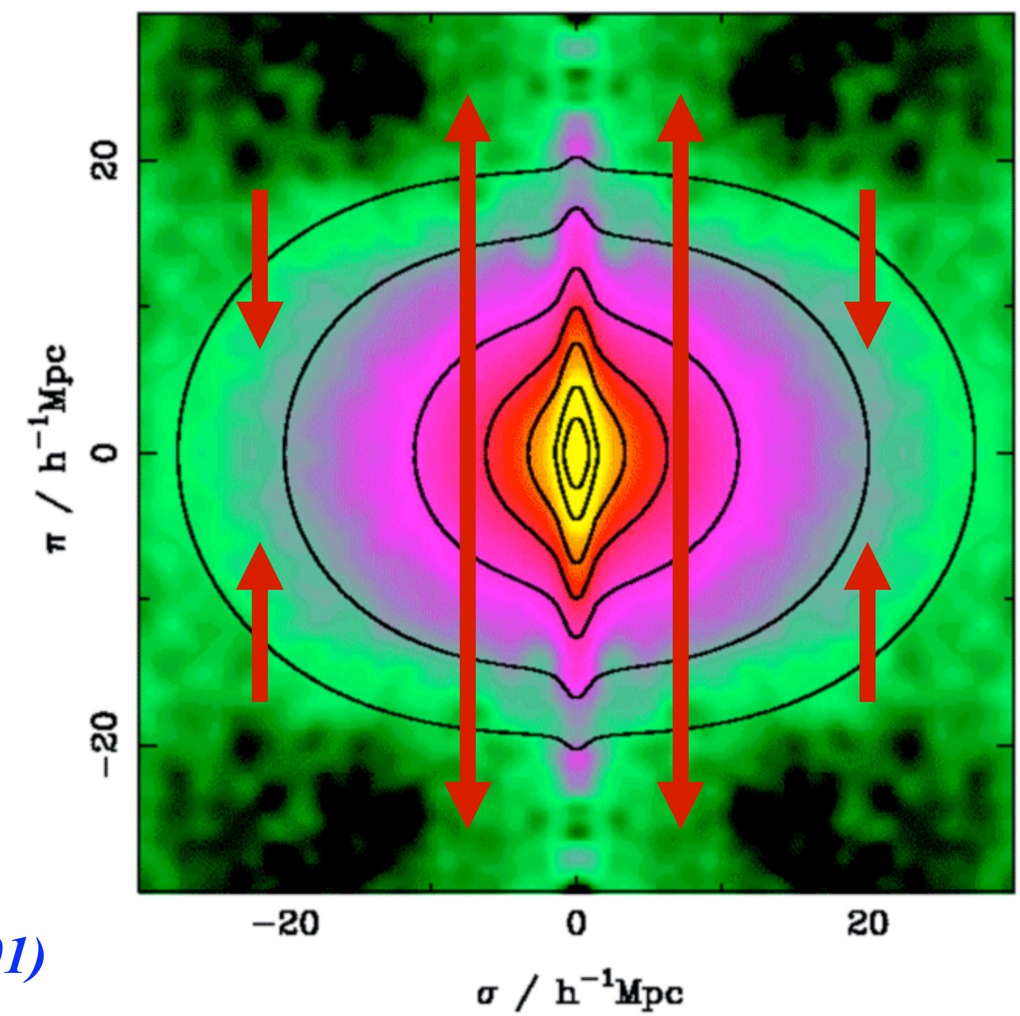
- peculiar velocities quantified by distribution of >100,000 galaxies
- Two effects visible:

  Small separations: 'Finger-of-God';

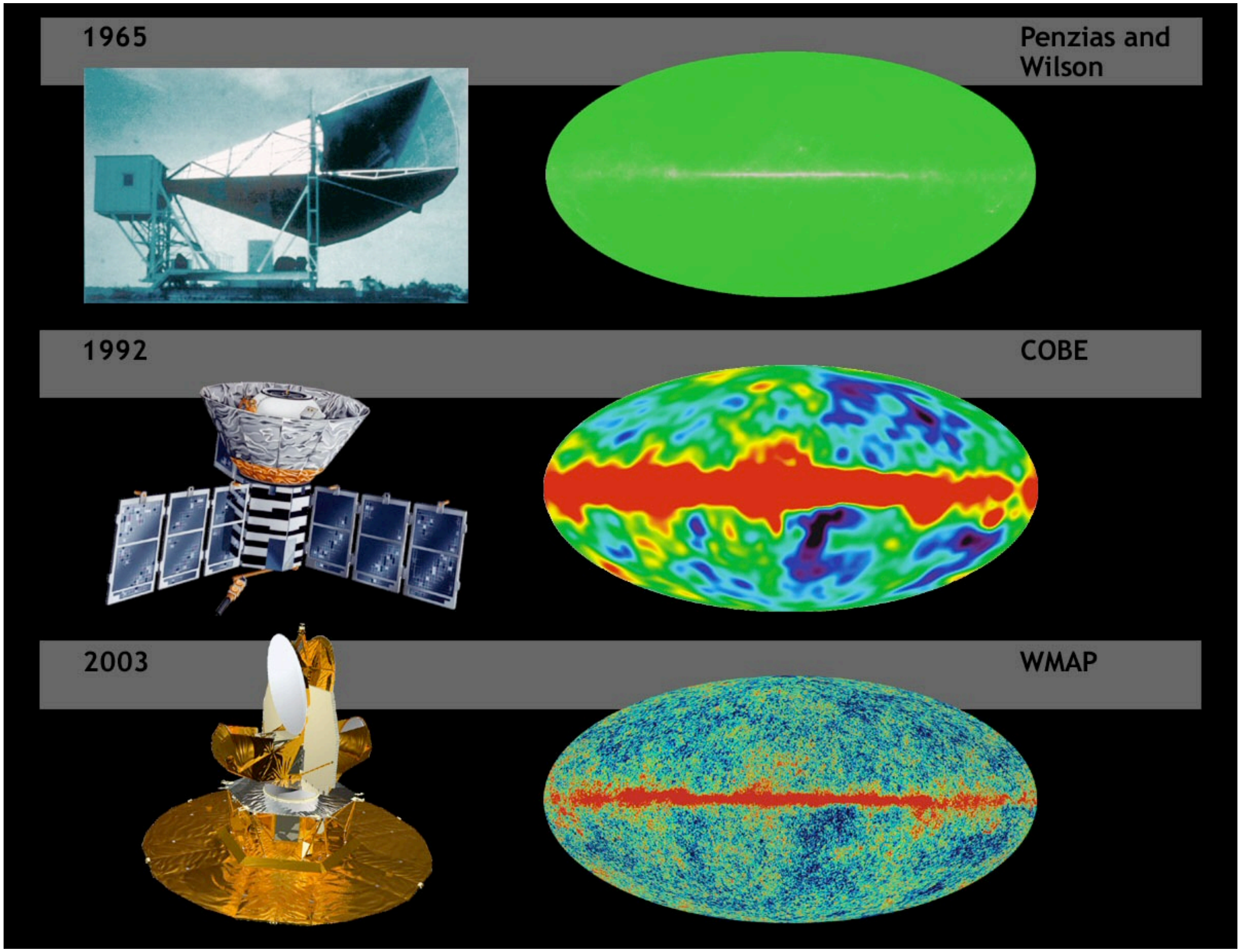
  Large separations: l.o.s. flattening

LOW MASS DENSITY

Peacock et al, Nature, 410, 169 (2001)

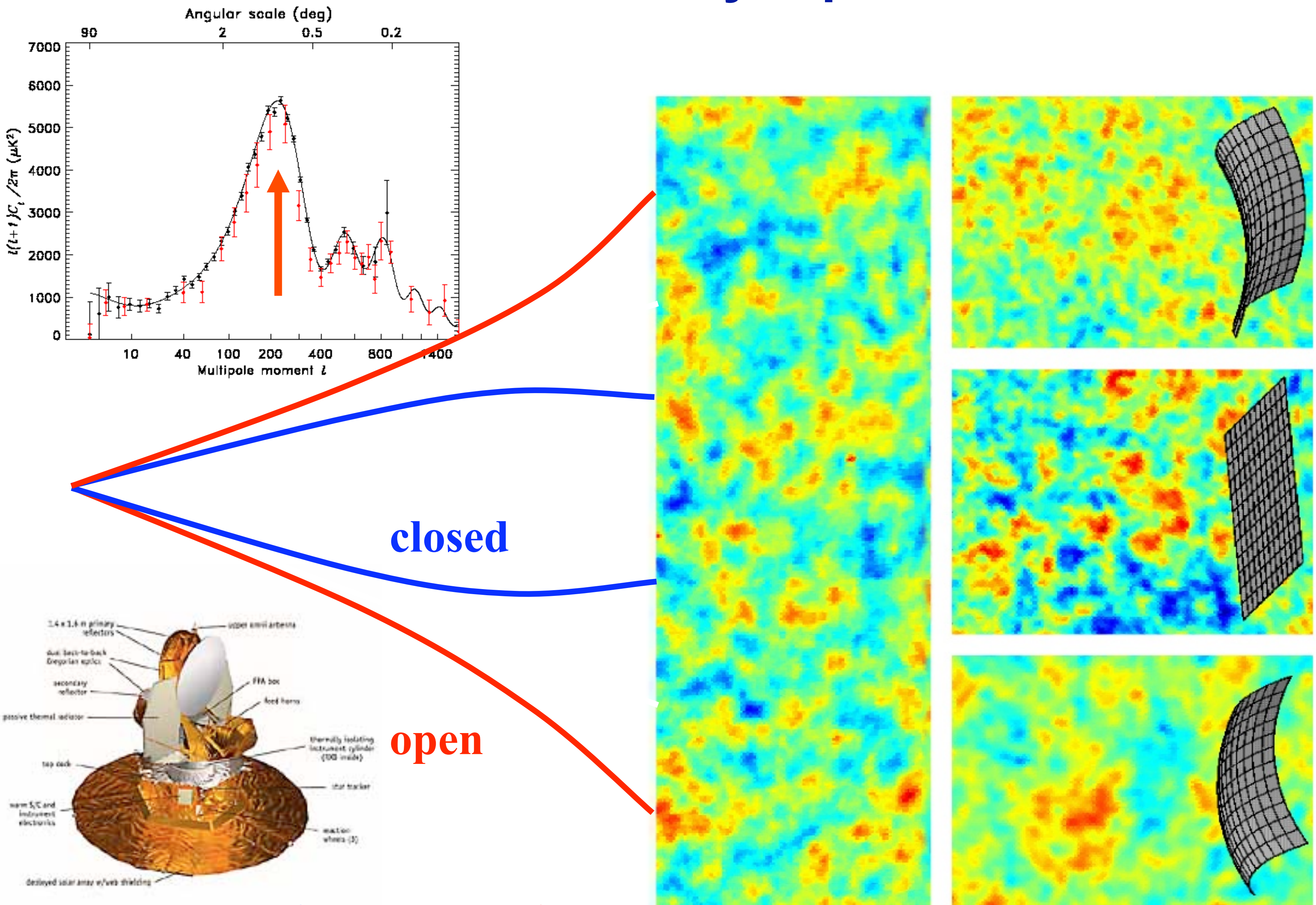


Progress in Cosmology: II - Microwave Background



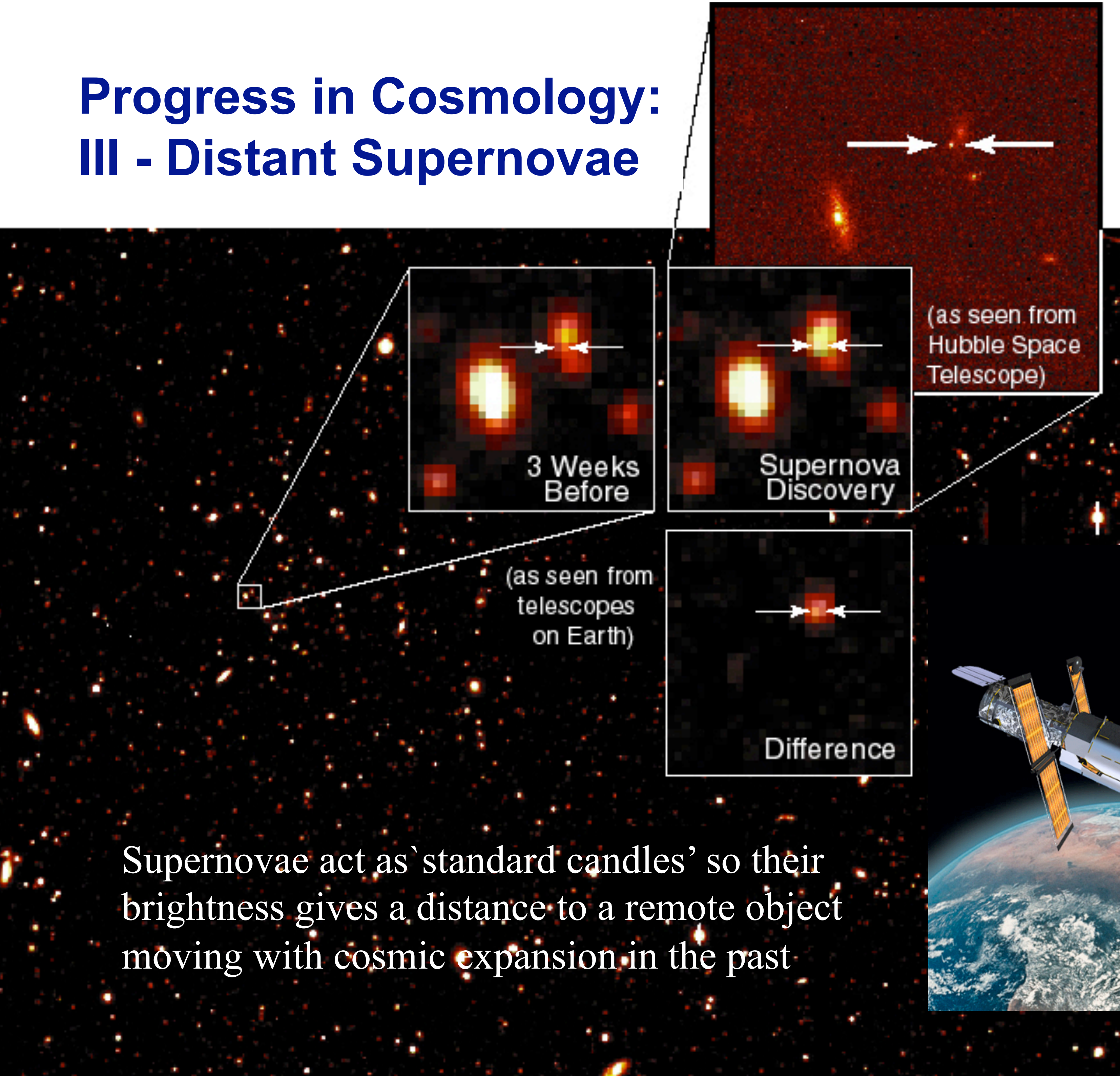
Microwave background corresponds to separation of matter & radiation at redshift z =1088 ±1 when age = 372,000 years

Cosmic Geometry: Space is Flat



Measures *total* energy density

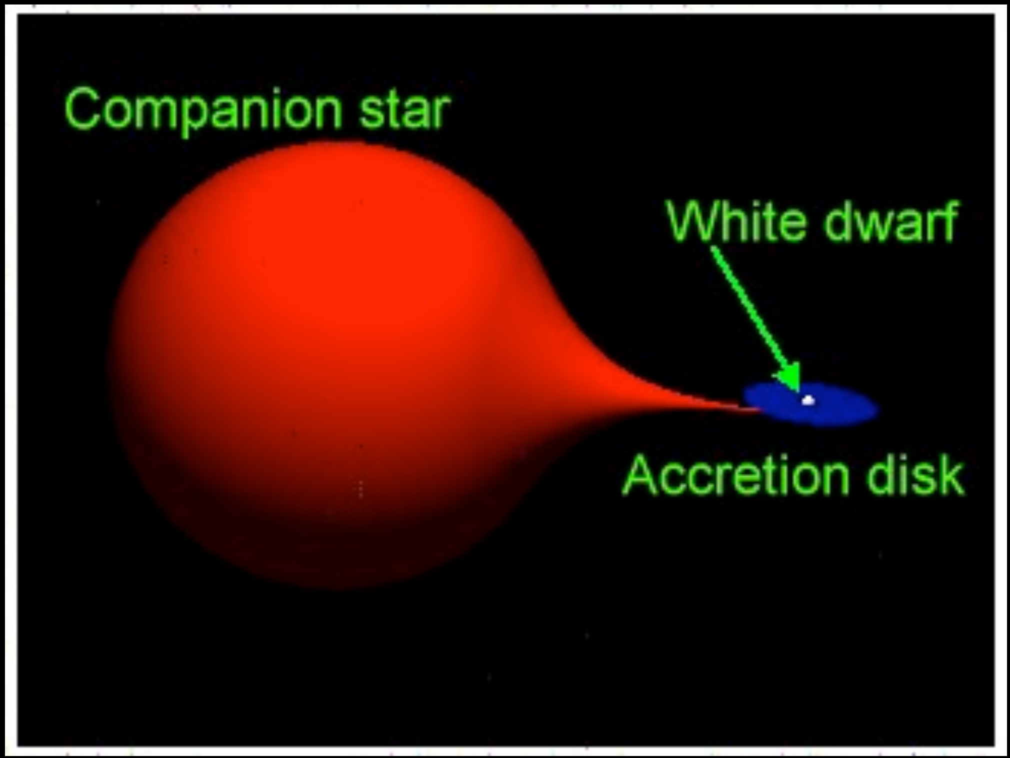
Progress in Cosmology:
III - Distant Supernovae

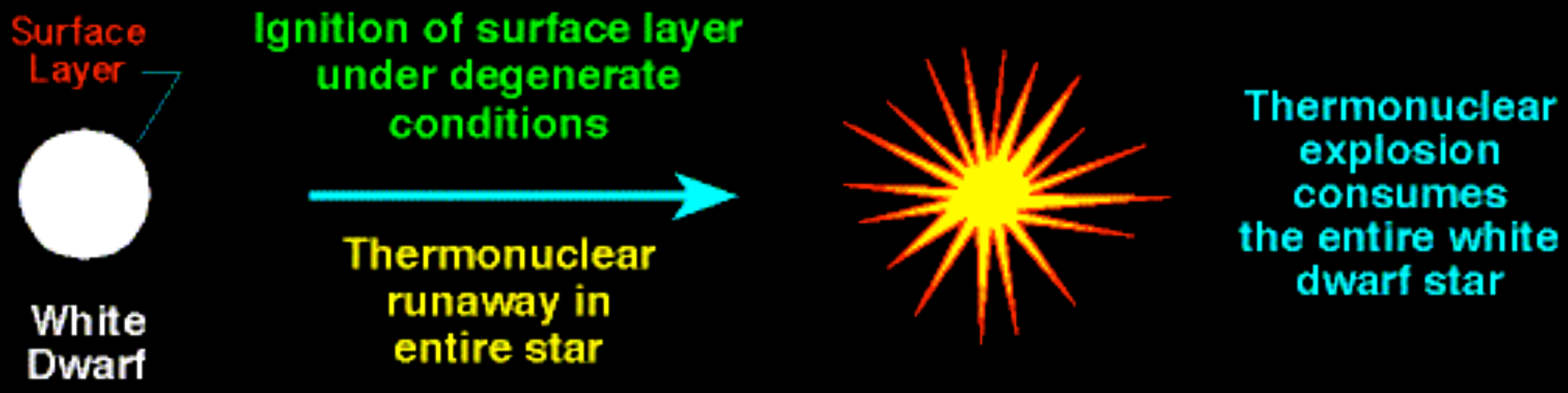


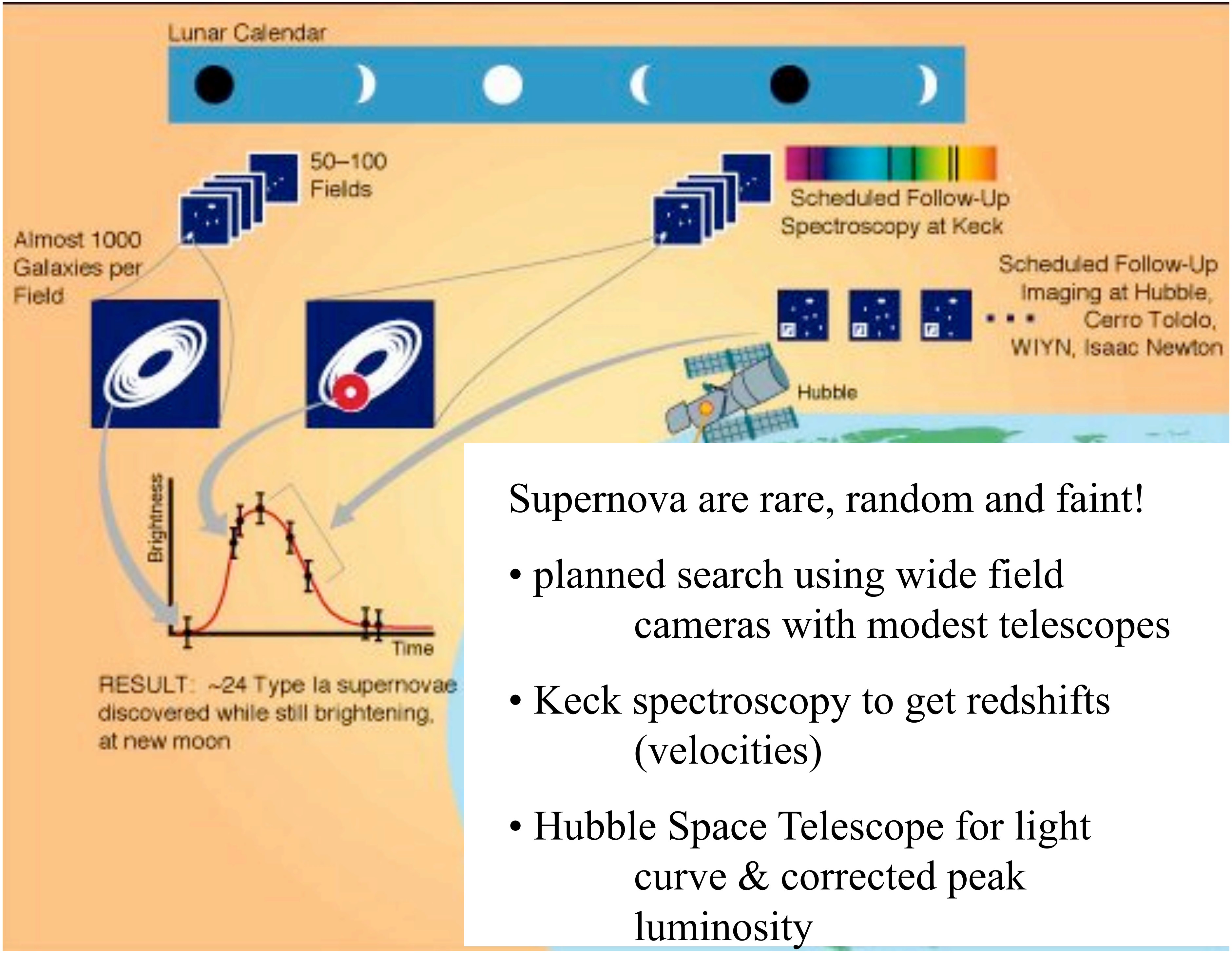
Supernovae act as`standard candles' so their brightness gives a distance to a remote object moving with cosmic expansion in the past

Type Ia Supernovae

Thought to occur in binary systems containing an accreting white dwarf; models suggest explosion is very homogeneous

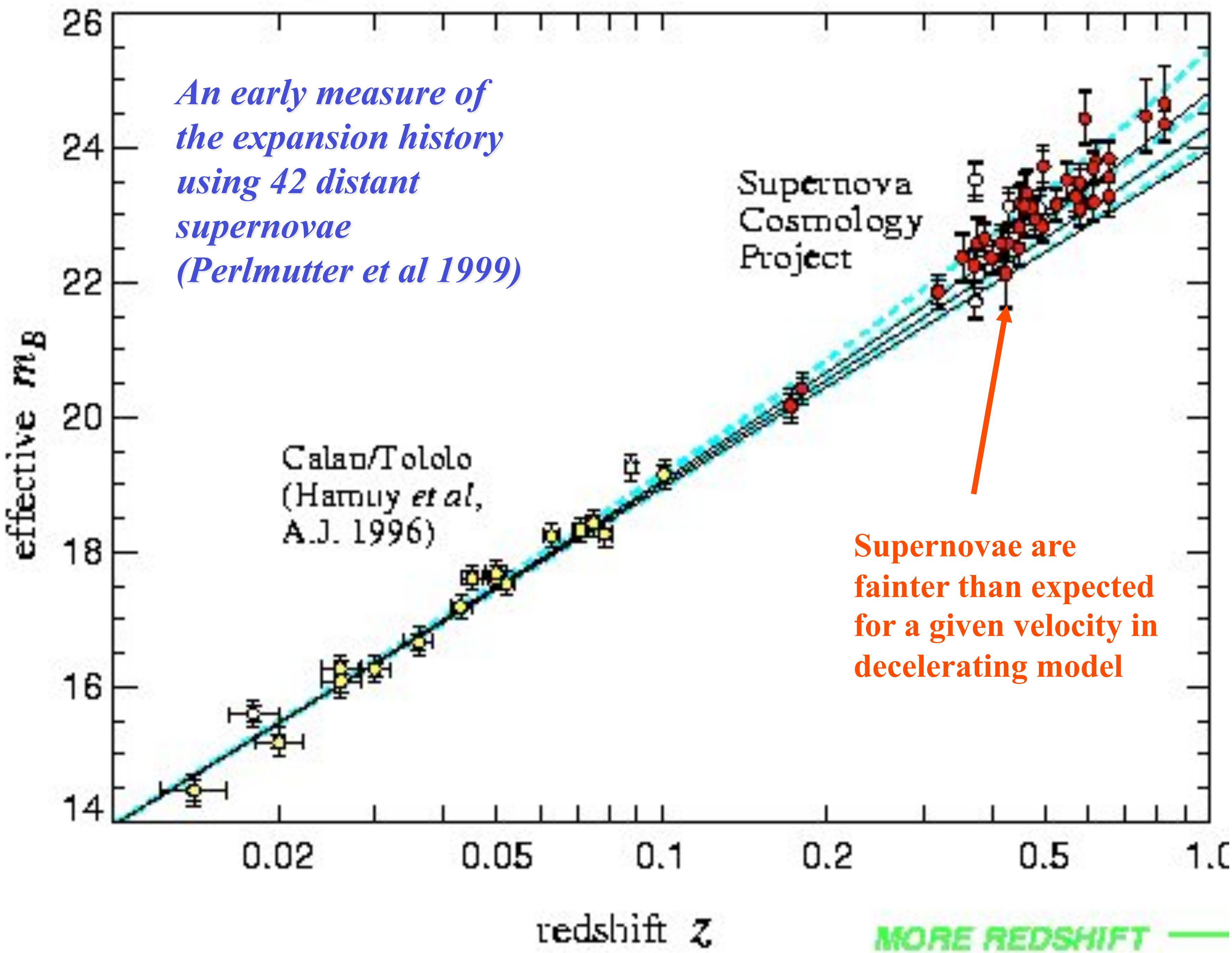






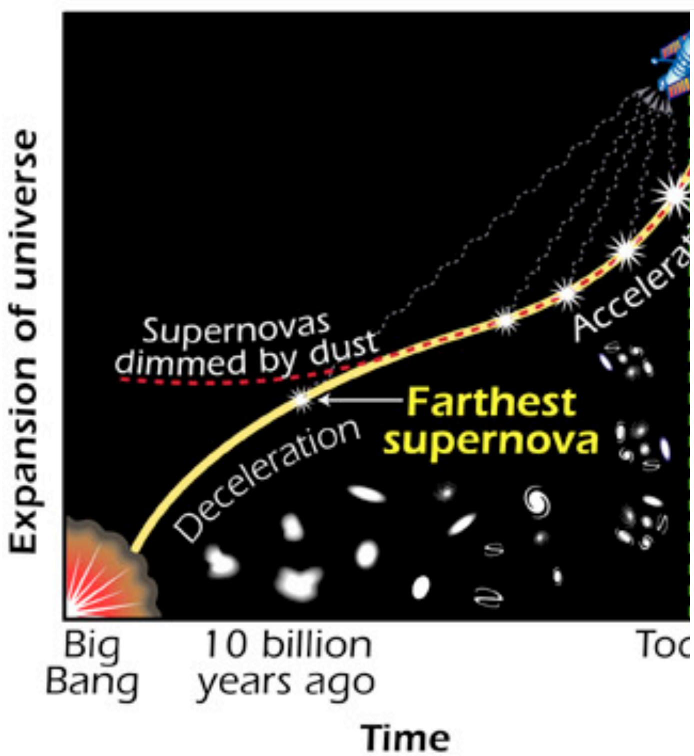
Supernova are rare, random and faint!

- planned search using wide field cameras with modest telescopes
- Keck spectroscopy to get redshifts (velocities)
- Hubble Space Telescope for light curve & corrected peak luminosity



An early measure of the expansion history using 42 distant supernovae (Perlmutter et al 1999)
Supernova Cosmology Project
Calan/Tololo (Hamuy et al, A.J. 1996)
Supernovae are fainter than expected for a given velocity in decelerating model
effective m_B
26
24
22
20
18
16
14
0.02
0.05
0.1
0.2
0.5
1.0
redshift z
MORE REDSHIFT

Cosmic Acceleration – a big surprise!



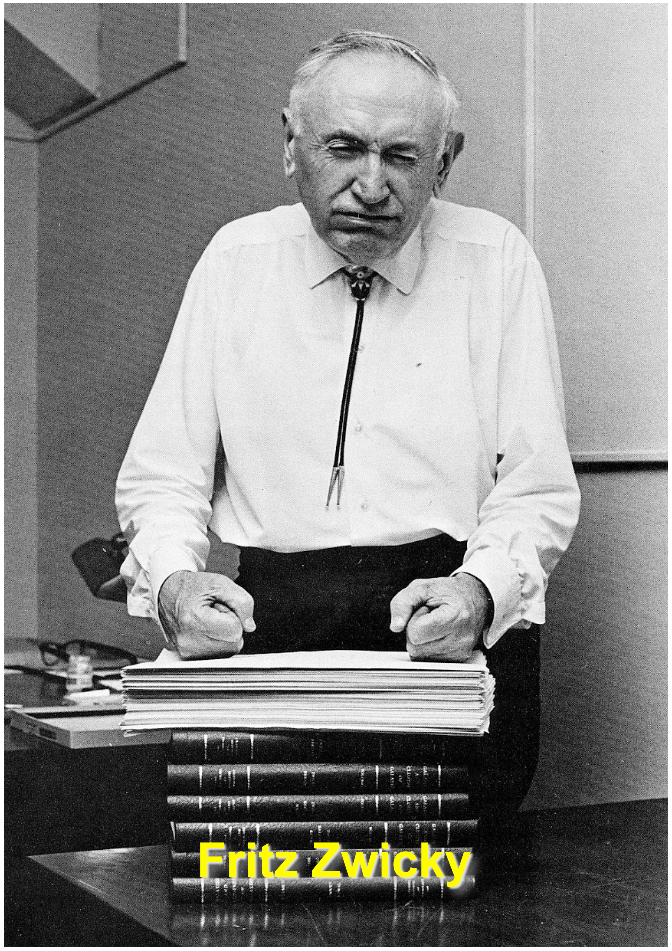
The rate of cosmic expansion is affected by two ingredients:

Matter – this gravitationally slows down the expansion but by an amount which varies as the density of matter is reduced

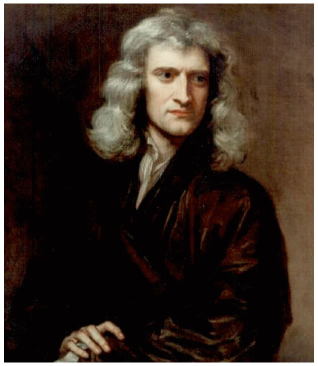
Dark energy – a more general explanation of unknown form which acts as a repulsive term (possibly equivalent to the original Λ term introduced by Einstein)

Two Rogue Cosmic Ingredients

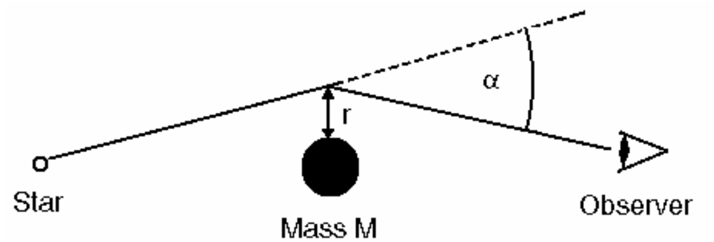
Dark Matter (1933 -)



Dark Energy (1998 -)



Deflection of Light by Mass



$$\delta = \frac{2\,G\,M}{Rc^2}$$

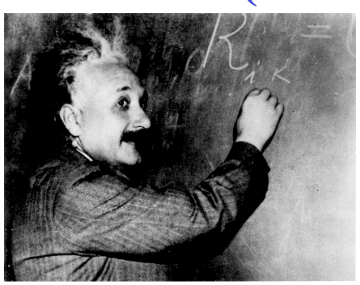
• Isaac Newton (1704) “Do not Bodies act upon Light at a distance, and by their action bend its Rays; and is not this action strongest at the least distance?”

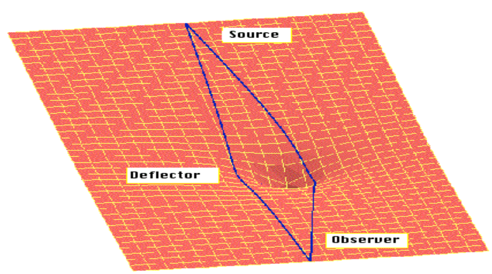
• Henry Cavendish (1784, unpublished) – calculates deflection due to hyperbolic trajectory assuming light is corpuscular

• Johann von Soldner (1804) – publishes same calculation and gets 0.84 arcsec

• Einstein (1911) – relativistic version of Newtonian deflection **0.875 arcsec** (classical result assumed light can be accelerated/decelerated like matter)

• Einstein (1915) – GR version includes curvature of space, **1.75 arcsec**



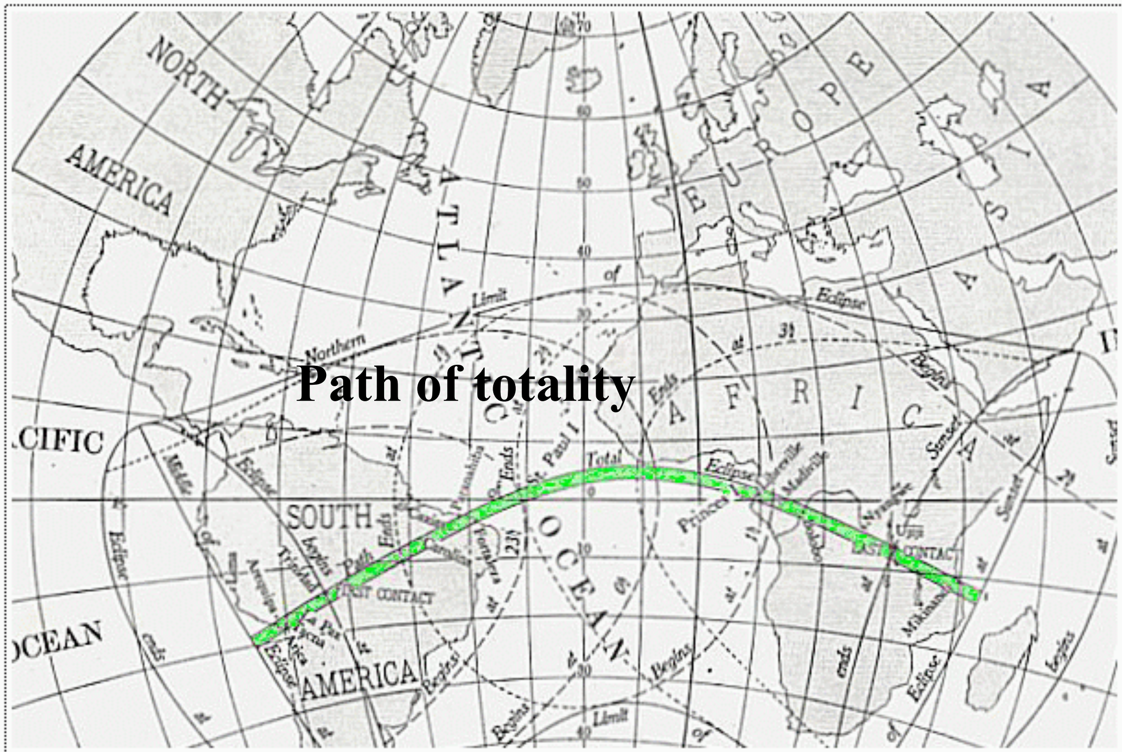


$$\delta = \frac{4\,G\,M}{Rc^2}$$

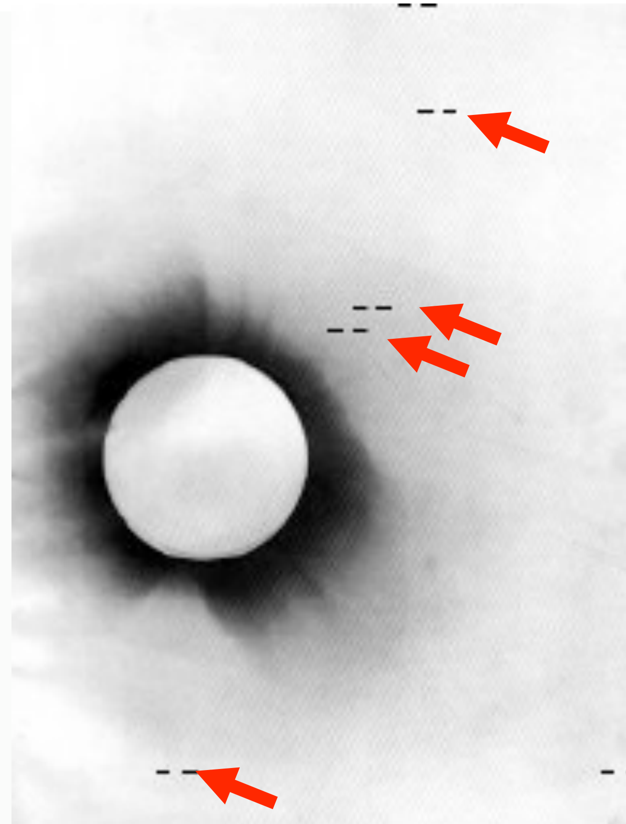
Solar Eclipse of 29 May 1919

Remarkable opportunity as Sun is in the rich Hyades star cluster

British send two expeditions to Sobral, Brazil and Principe, W Africa



The path of the 1919 eclipse.



Frank Dyson (Astronomer Royal) recognizes the opportunity
Eddington is however driving force as he is inspired by Einstein's theory
Eddington leads expedition by going to Principe

The unexpected hero: Arthur Eddington

When the eclipse expedition is planned, Britain is at war with Germany

Contact between Eddington and Einstein would be a `treasonable act’

Eddington learns of GR via de Sitter and is inspired to verify or disprove it

Eddington is a pacifist and a Quaker and is only rescued from military service by leading the expedition

The war ends 6 months before the eclipse

Kayes
Tambacounda
Bamako
Kédougou
Niamey
Maradi
Zinder
Sokoto
Katsina
Kano
Burkina Faso
N'Djamena
Maiduguri
Abéché
Bobo-Dioulasso
Guinea
Bouna
Sierra Leone
Côte d'Ivoire
Daloa
Yamoussoukro
Liberia
Monrovia
Abidjan
Divo
Sekondi-
Garoua
Sarh
Central African Republic
Bouar
Bambari
Abong Mbang
Bangui
Gemena
Lisala
Basankusu
Mbandaka
Boende
Congo (Brazzaville)
Inongo
Bandundu
Brazzaville
Pointe-Noire
Kikwit
Matadi
Mbanga Ngungu
Uige
Luanda
Ndalatando
Malange
Saurimo
Sumbe
Luena
ILHA DE PRÍNCIPE
SETE PEDRAS
ILHÉU BOMBOM
PONTA DE RUBEIRA IZÉ
PRAIA DE STA RITA
PRAIA DAS BURRAS
PONTA MÃE MARTA
BELO MONTE
PONTA GRANDE
STA RITA
SUNDY
PACIÊNCIA
PONTA CAPITÃO
ILHÉU SANTANA
PRAIA INHAME
BAÍA DE STO ANTÓNIO
PONTA DO SOL
STO ANTÓNIO
HOSPITAL VELHO
PONTA DE PRAIA SALGADA
NOVA CUBA
PRAINHA
MONTALEGRE
STO CRISTO
NOVA ESTRELA
ABADE
PONTA DA GRAÇA
BAÍA DAS AGULHAS
BELA VISTA
PORTO REAL
PRAIA PERIGUITO
PRAIA BAMBÚ
PORTELA DO LUMIAR
MORRO LESTE
PICO DE PRÍNCIPE
CAIS GENERAL FONSECA
PRAIA CABINDA
PRAIA DE S. TOMÉ
NEVES FERREIRA
PRAIA GRANDE
PONTA CAFÉ
ILHÉU PORTINHO
PONTA DO PICO NEGRO
OCEANO ATLÂNTICO
ILHÉU BONÉ DE JÓQUEI

Pilgrimage to Principe: September 2008

Arthur Stanley Eddington to Sarah Ann Eddington,
29 April–2 May 1919

Roça Sundy | Principe
Tuesday April 29.

My very dear Mother

Just a month to the eclipse; and today we have all our belongings at the site selected, and have started the work of erection.

We got our first sight of Principe at 9 o'clock in the morning of April 23, and it looked very charming. We had seen no land since leaving Cape Verde Islands; although we went within forty miles or so of Africa, it was always too misty to see the coast. We did not pass any ships. Occasionally we saw schools of porpoises playing about, and plenty of flying-fish, but no whales or sharks.

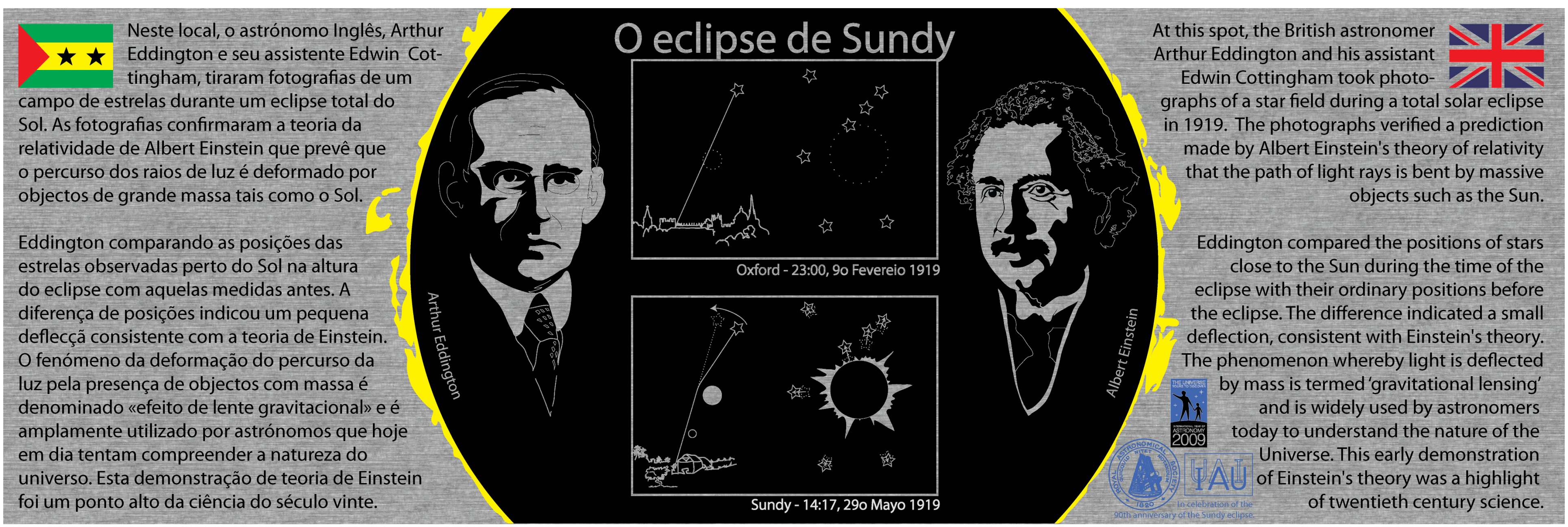
At four o'clock that afternoon we both played tennis with the Curador and the Judge. We had three very good sets and enjoyed the games very much. The court was on asphalte. There is no one else who plays tennis on the island now, so I think the other two were very glad to have the game—the Judge especially seemed to enjoy himself. I expect we shall get some more games when we return to the city.[2] (We always call it the city—but S. Antonio is only a tiny village.)

IYA2009: Celebrating 90 Years of General Relativity

May 29th 2009 Principe
- Unveiling new plaque
- Lectures/poster displays
- High school activities

Sponsors: IAU, RAS, Gulbenkian Foundation, Rombout Swanborn

http://www.1919eclipse.org/



Fritz Zwicky: the irascible pioneer

Contrary to proclamations by Einstein, Eddington and others, Zwicky (1936) predicts gravitational lensing will be invaluable in:

• tracing and measuring the amount of dark matter thought to pervade the cosmos

• magnifying distant objects

Never lived to see the renaissance..

How it works: three broad regimes

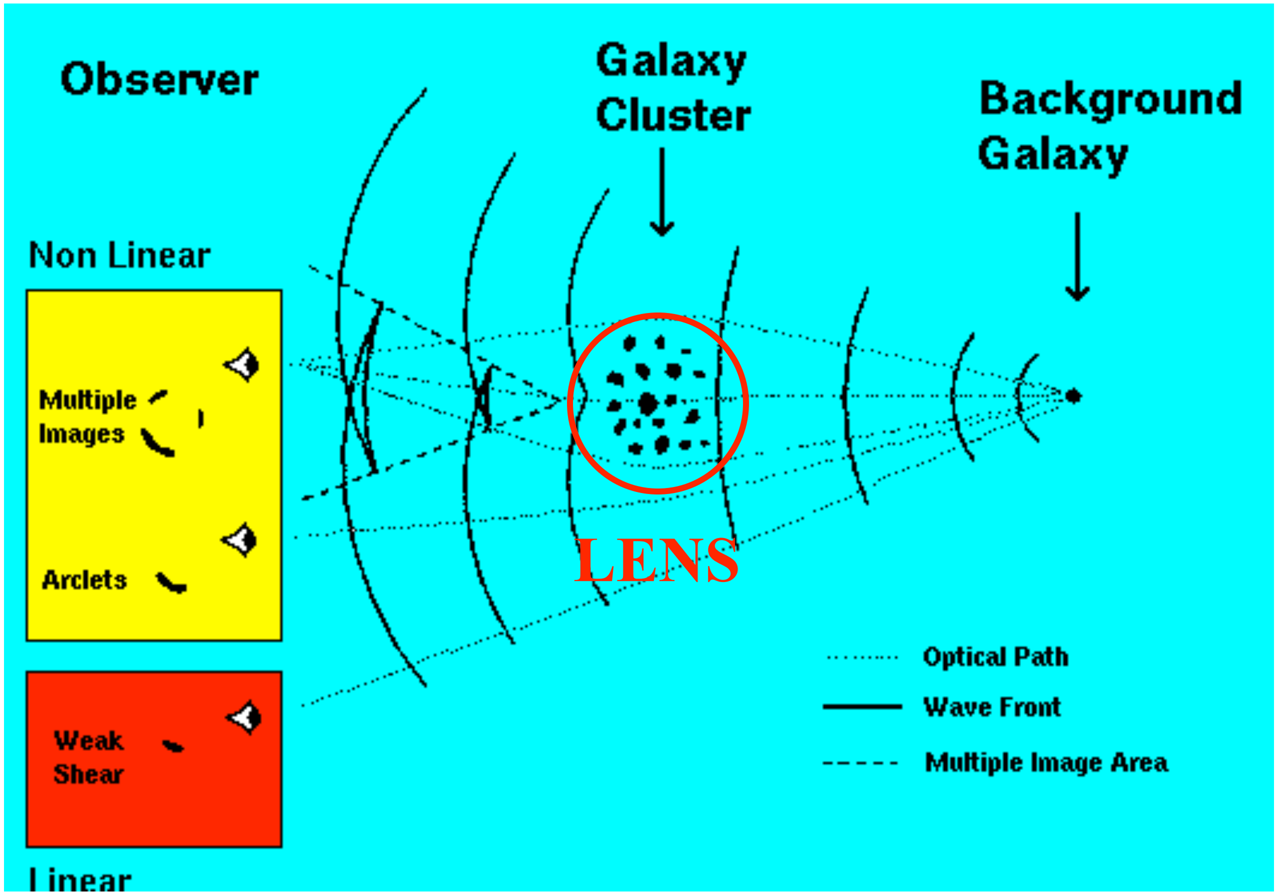
• rings & arcs

↓

•arclets

↓

• weak distortion

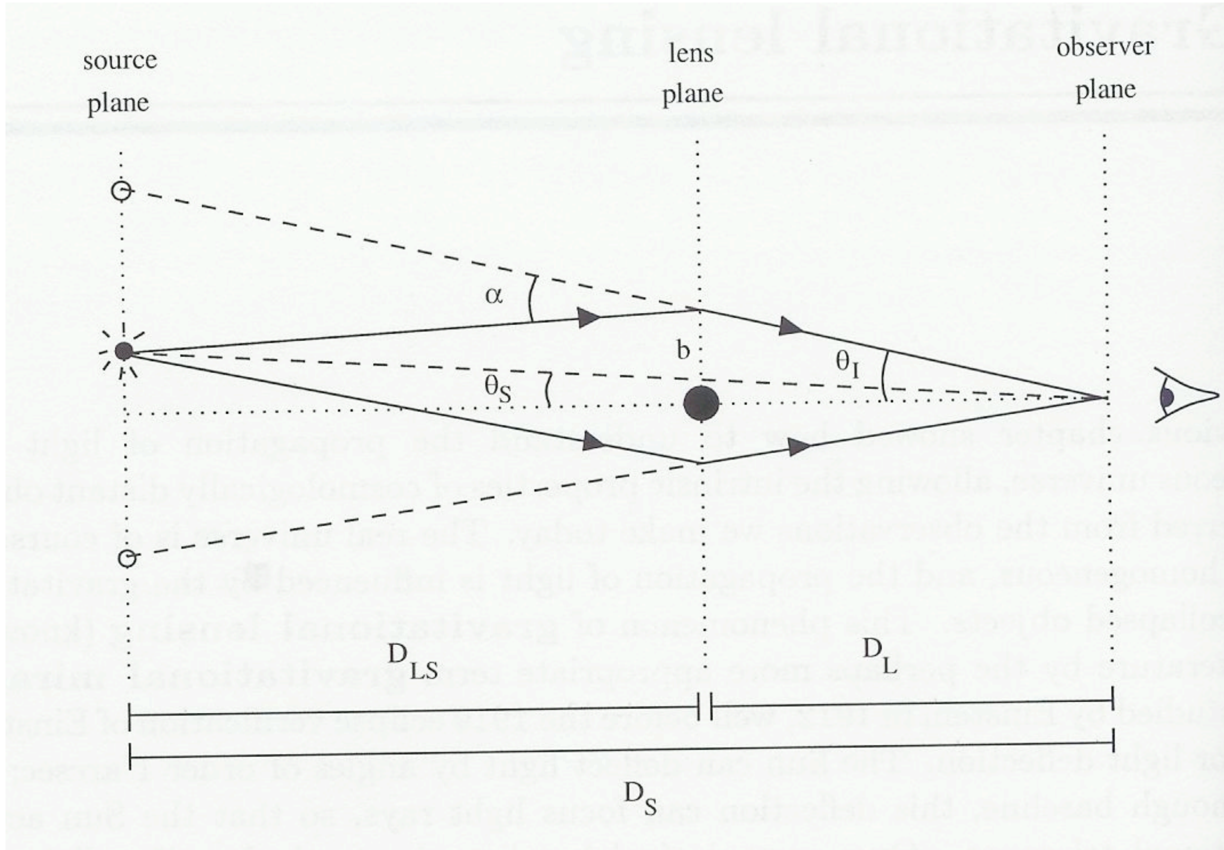


What the observer sees, viewing through a lens, depends on the focusing power of the lens, the relative distances of lens and background source and the degree of alignment of both

Basics of Gravitational Lensing

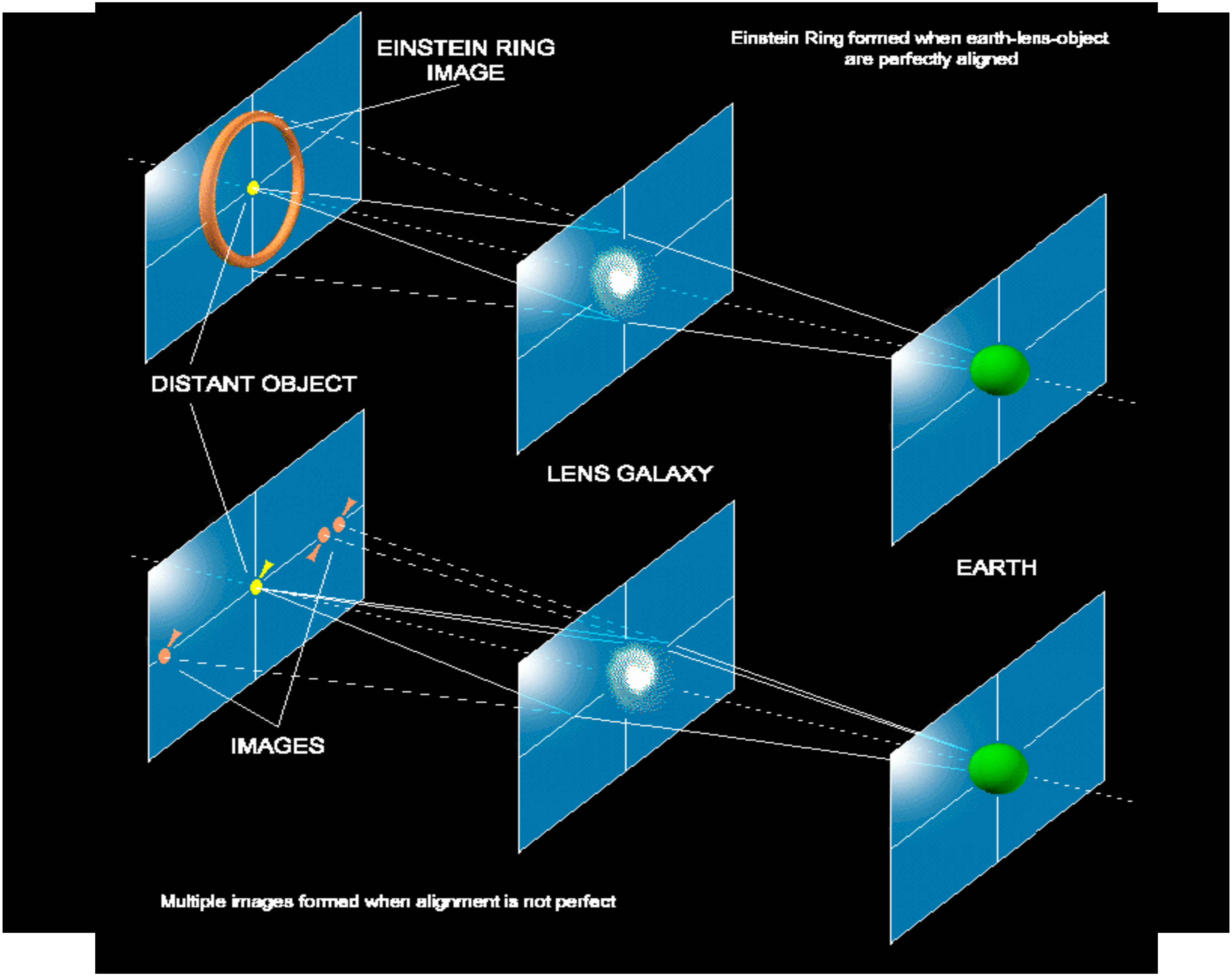
Thin lens approximation:

ϑ_I, ϑ_S represent positions on image & source plane, α is deflection

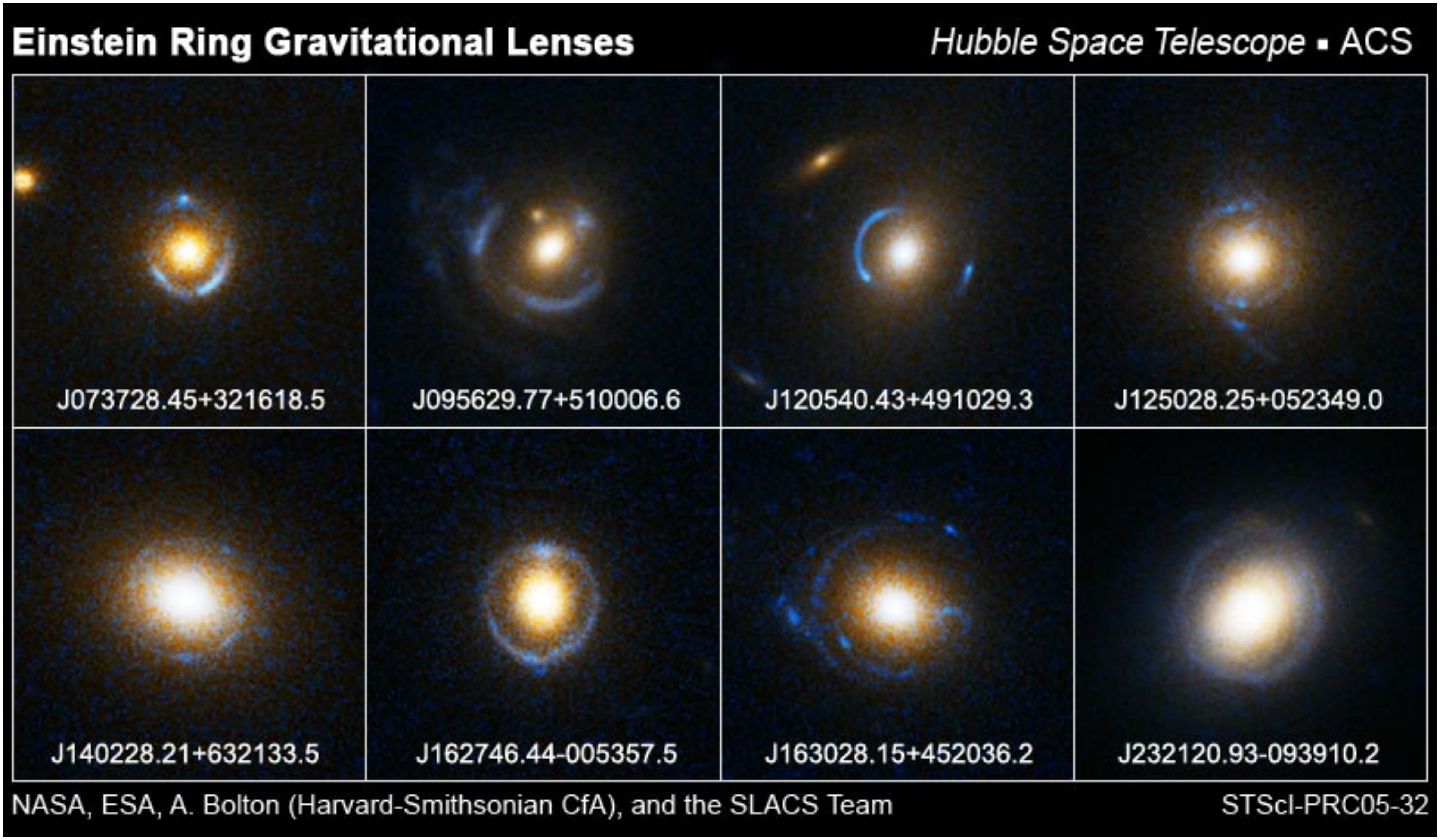


Geometric lens equation relevant in weak regime where 1-to-1 mapping is ok

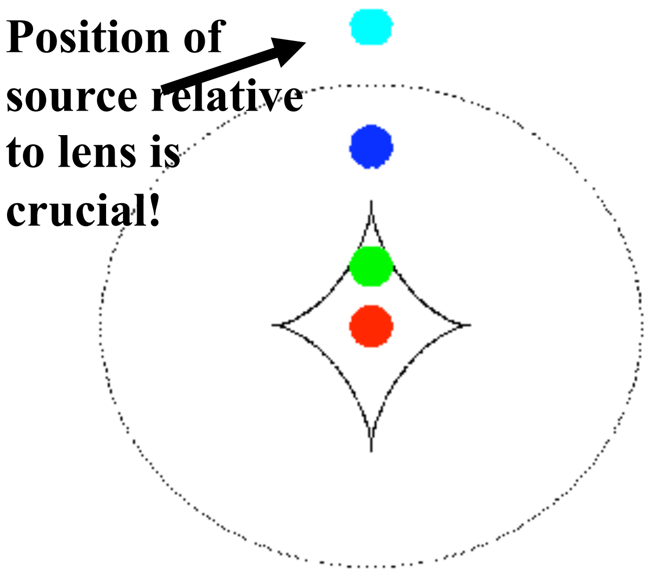
$$\alpha(D_L\theta_I) = \frac{D_S}{D_{LS}}(\theta_I - \theta_S),$$


EINSTEIN RING IMAGE
Einstein Ring formed when earth-lens-object are perfectly aligned
DISTANT OBJECT
LENS GALAXY
EARTH
IMAGES
Multiple images formed when alignment is not perfect

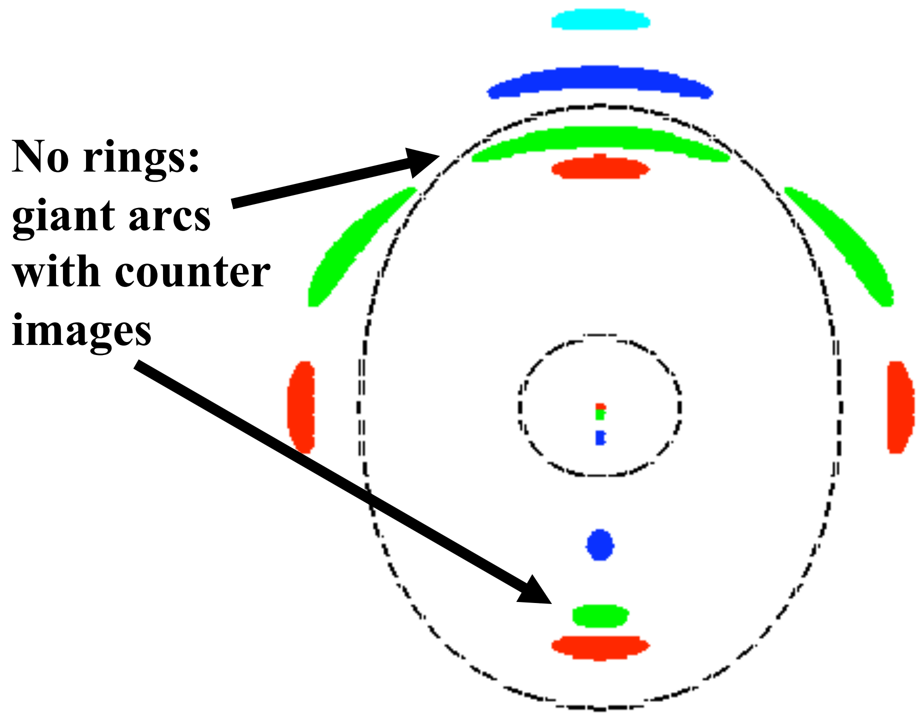
Hubble Survey for Einstein Rings



More Complicated Strong Lenses



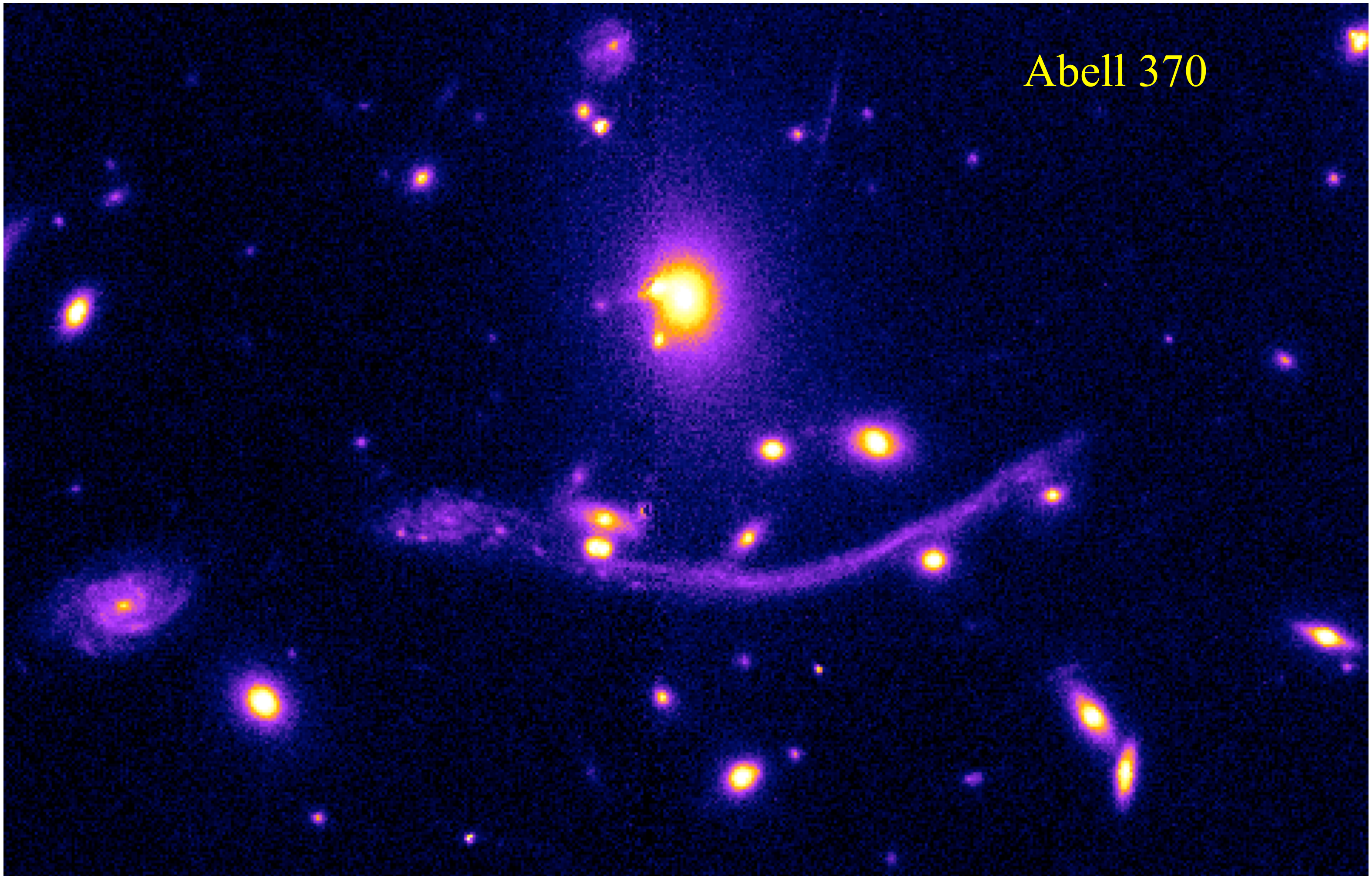
The Real Sky



What Observer Sees

In case of elliptical lens, no ring is produced, but as background source moves closer in alignment, multiple images, some highly magnified appear – these are known as “giant arcs”

The First Giant Arc Seen in a Cluster of Galaxies

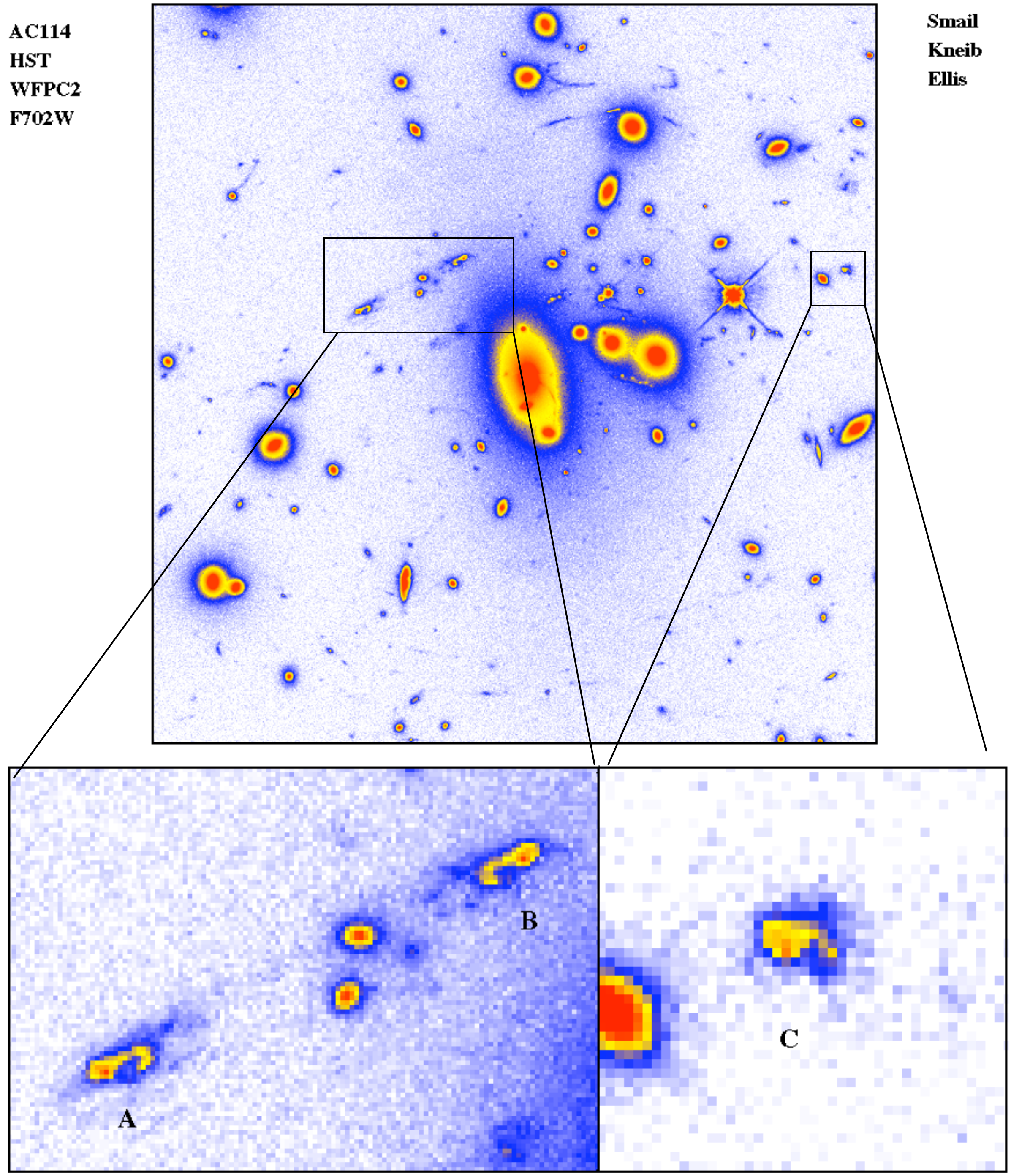


In 1987 Genevieve Soucail at Observatoire de Midi Pyrenees (Toulouse) demonstrated the arc in the galaxy cluster Abell 370 represents light of a single background galaxy distorted by the foreground cluster lens

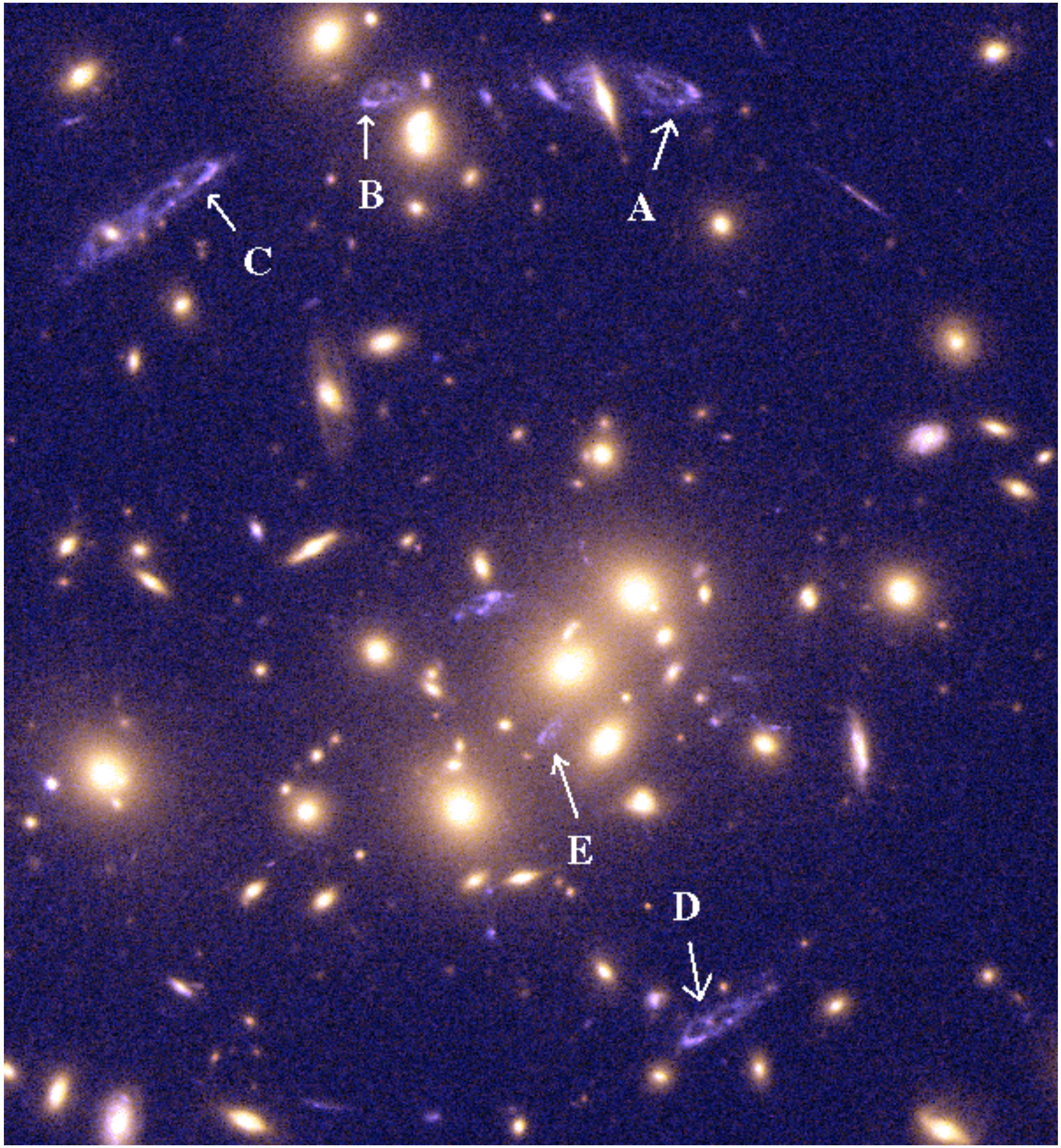
Multiple Images

The exquisite resolution of Hubble locates same source seen in 3 different locations!

This is particularly informative if the distances to the lens and the source can be determined as it tells us how lensing matter is distributed in the cluster.



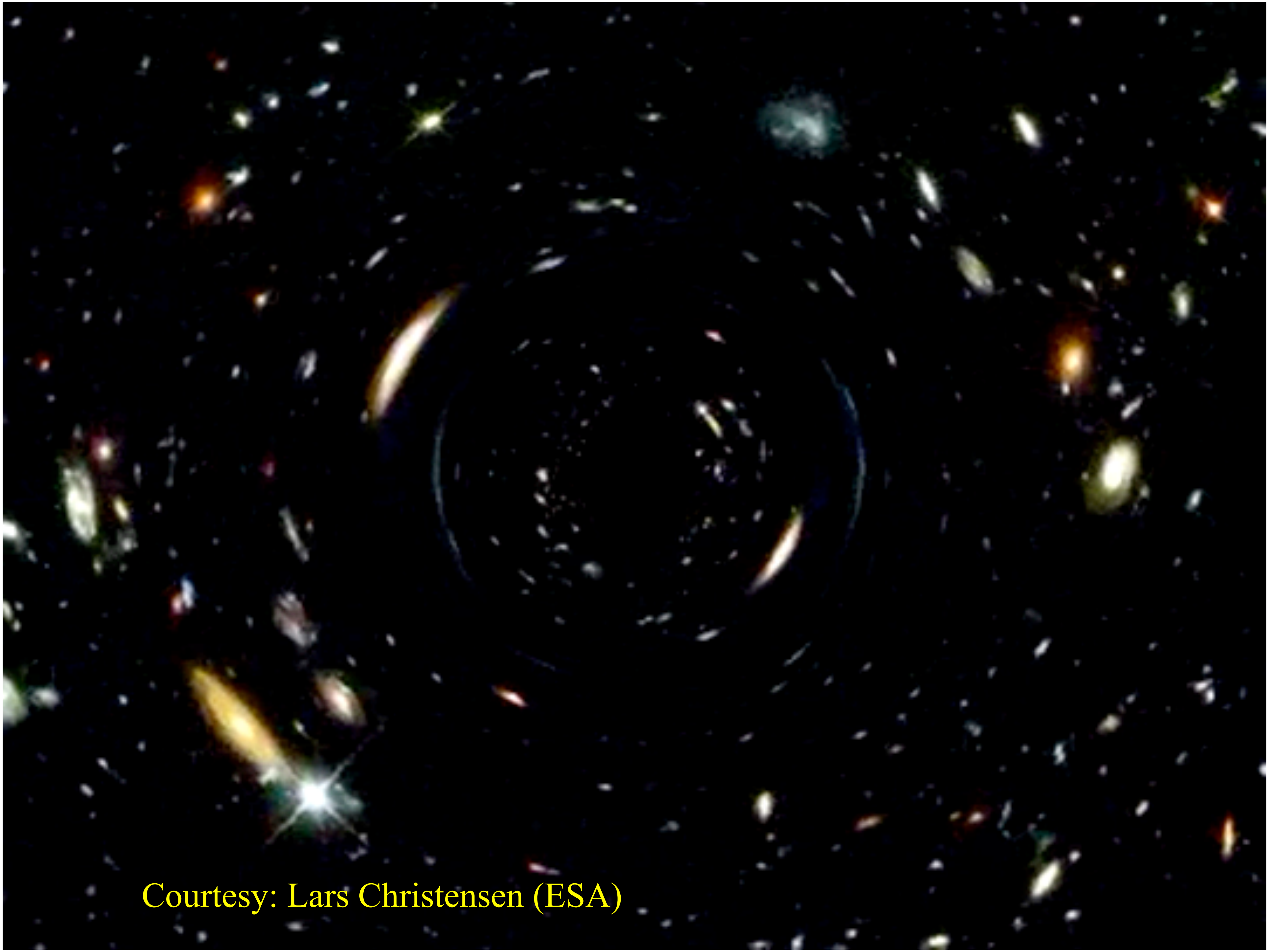
Cl0024+16



A remarkable cluster lens:

5 images of the same source (A-E)!


Abell 2218: arcs galore!


Courtesy: Lars Christensen (ESA)

The Role of Lensing in Cosmology

I: - Strong lensing: multiply-imaged sources tests "universal" mass profile predicted in cold dark matter models; is DM non-interacting?

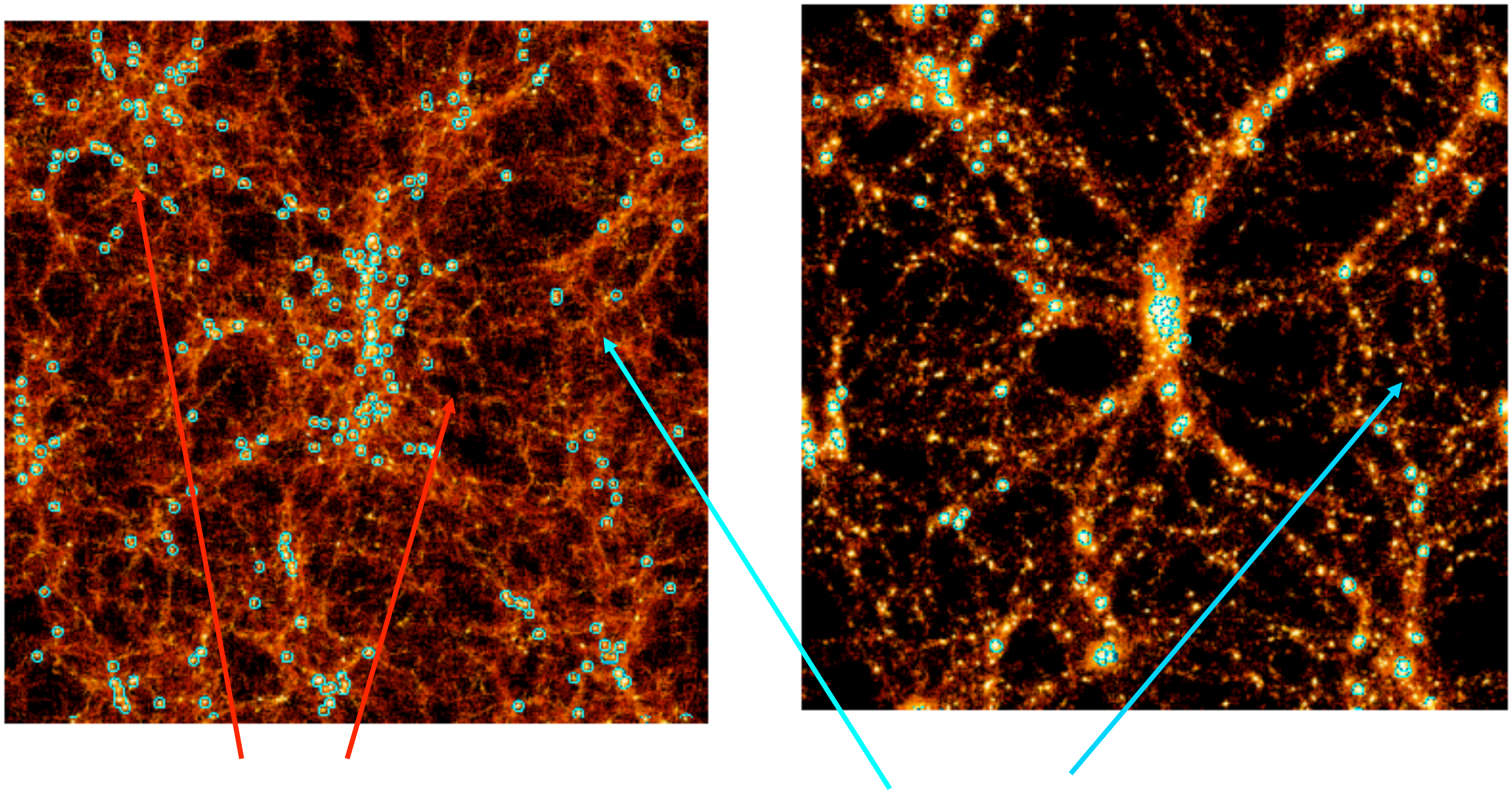
II: - Weak lensing: statistical characterization of DM distribution; its evolution provides strong constraint on dark energy (independently of supernovae & with less assumptions)

III: - Strong magnification: use of cluster lenses as "natural telescopes" to survey distant Universe; magnify distant galaxies and set limits on epoch of "first light" stellar systems; likewise search for Earth-like planets around stars in Milky Way

..governs the formation of galaxies

12 billion years ago

Present epoch



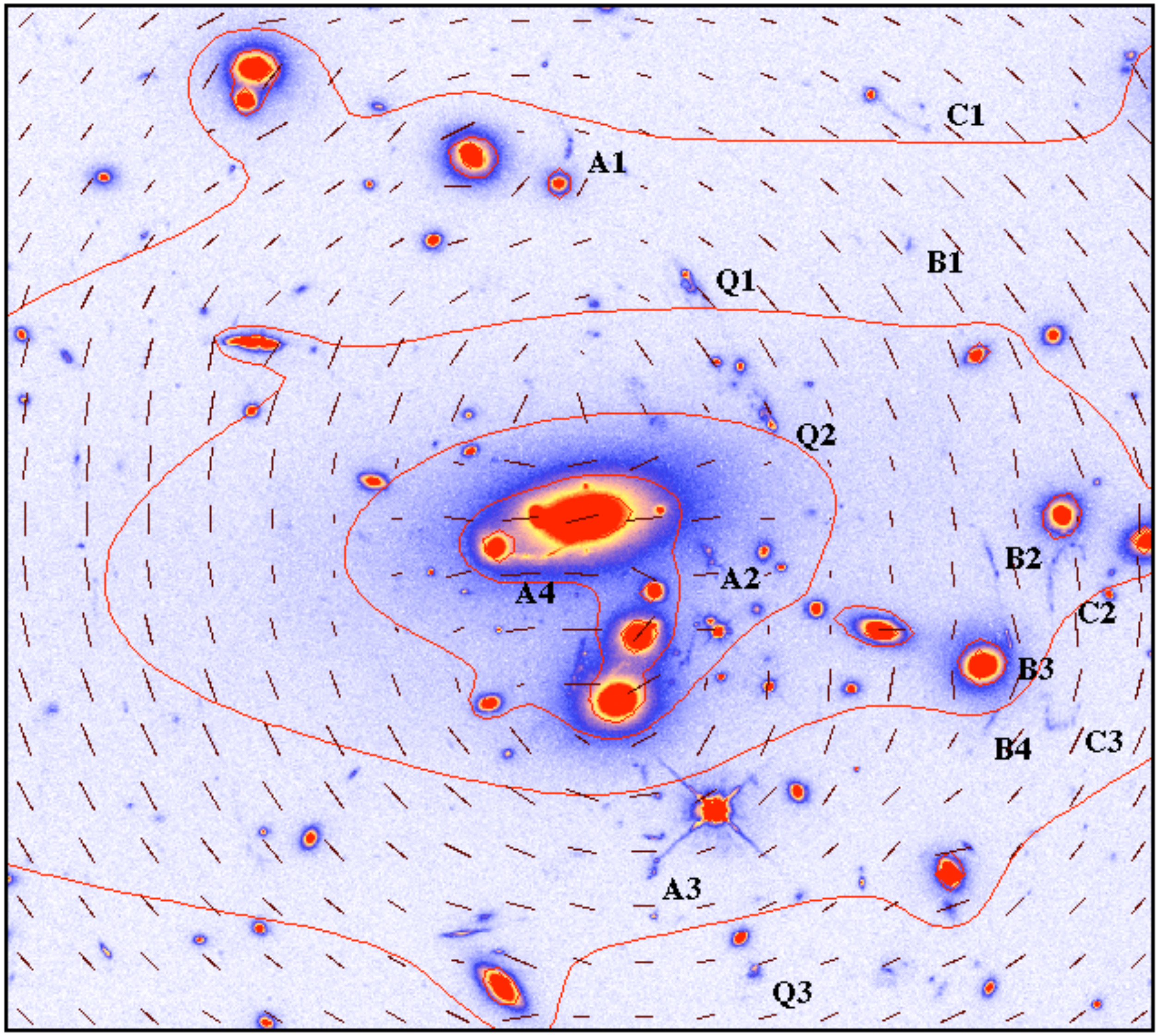
Dark "halos" act as seeds for later stars and galaxies to form

Analysis of Multiple Images with Hubble

We find the dark matter is:

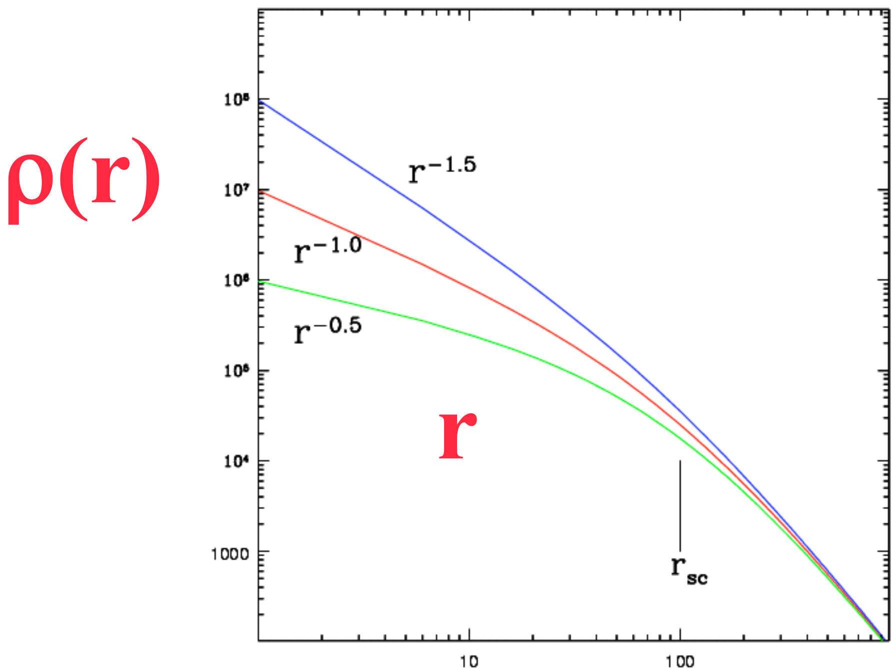
• dominant (50-100 times more than the mass associated with the visible cluster galaxies)

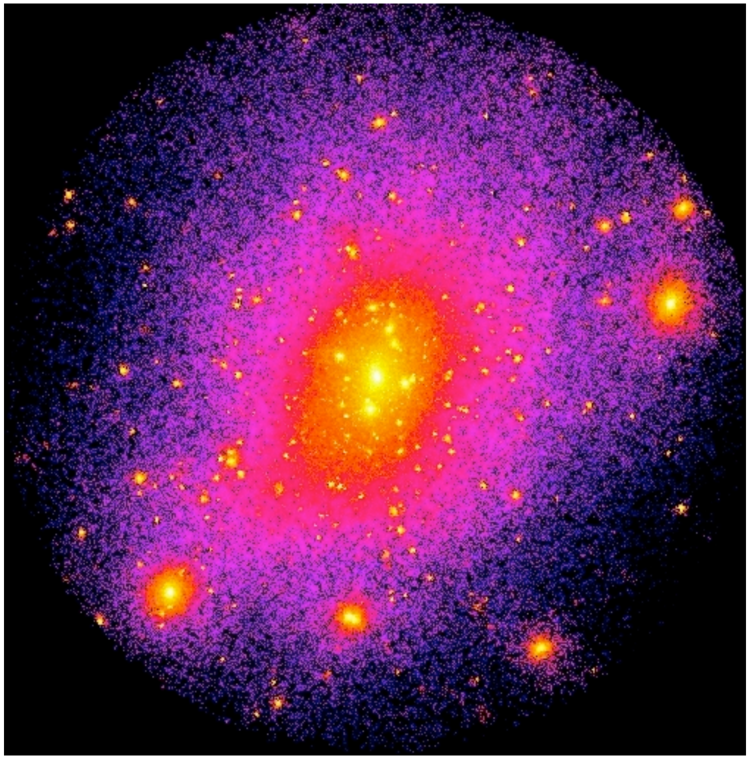
• smoothly distributed, broadly following that of the smoothed light



AC114 HST/WFPC2 Smail, Kneib, Ellis 96

Nature of Dark Matter: Universal Profile?

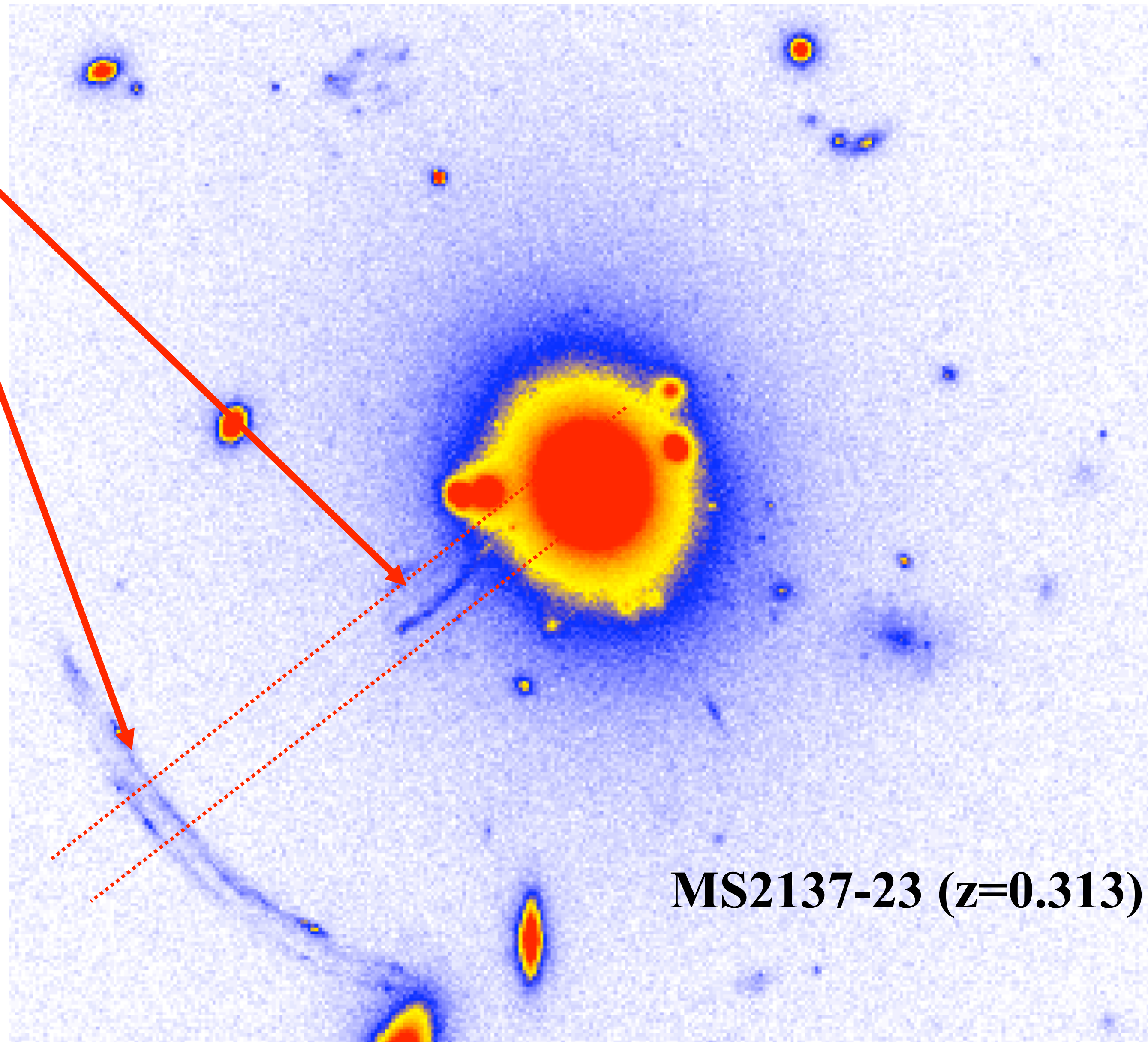




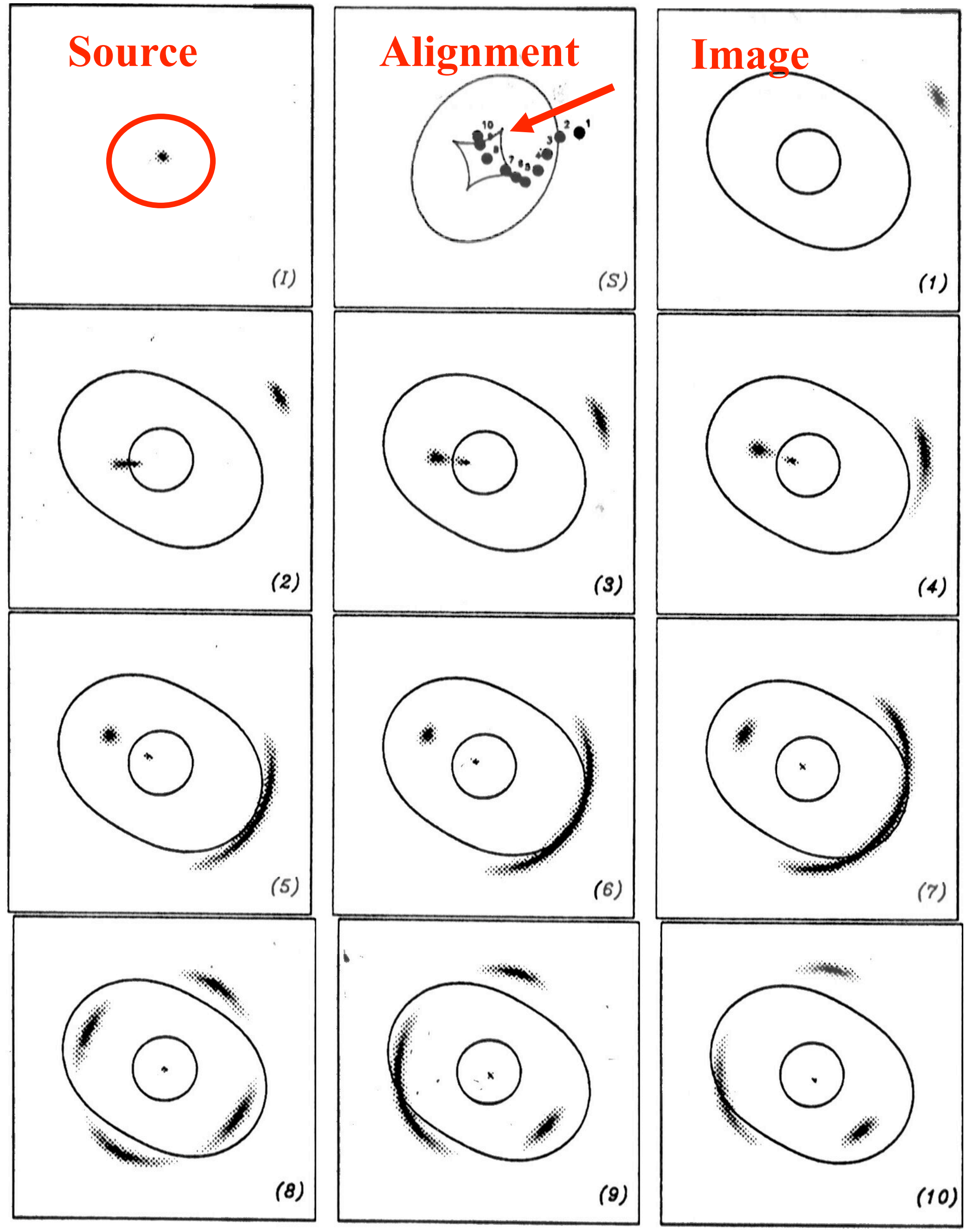
- **Theorists claim Cold (non-interacting) Dark Matter concentrates with a density profile with radius $\rho_D \propto r^{-\beta}$ with simulations indicating "universal" form: 1.0 <β <1.5**
- **Can gravitational lensing be used to test how dark matter is distributed on these scales ?**

Mass profiles in cluster cores

Presence of *radial and tangential* arcs of known z strongly constrains mass on 20-50 kpc scales

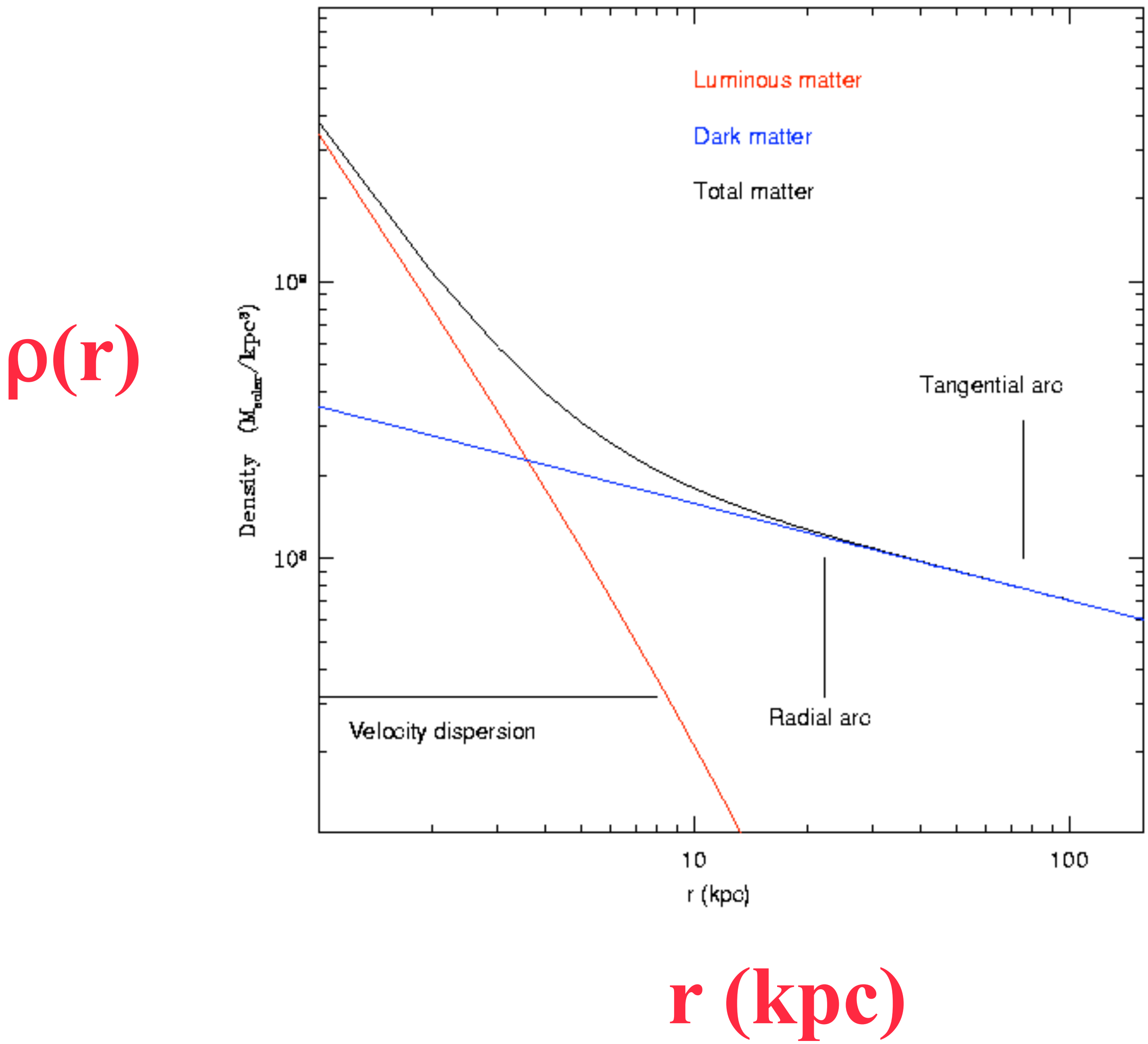


Arcs & Multiple Images

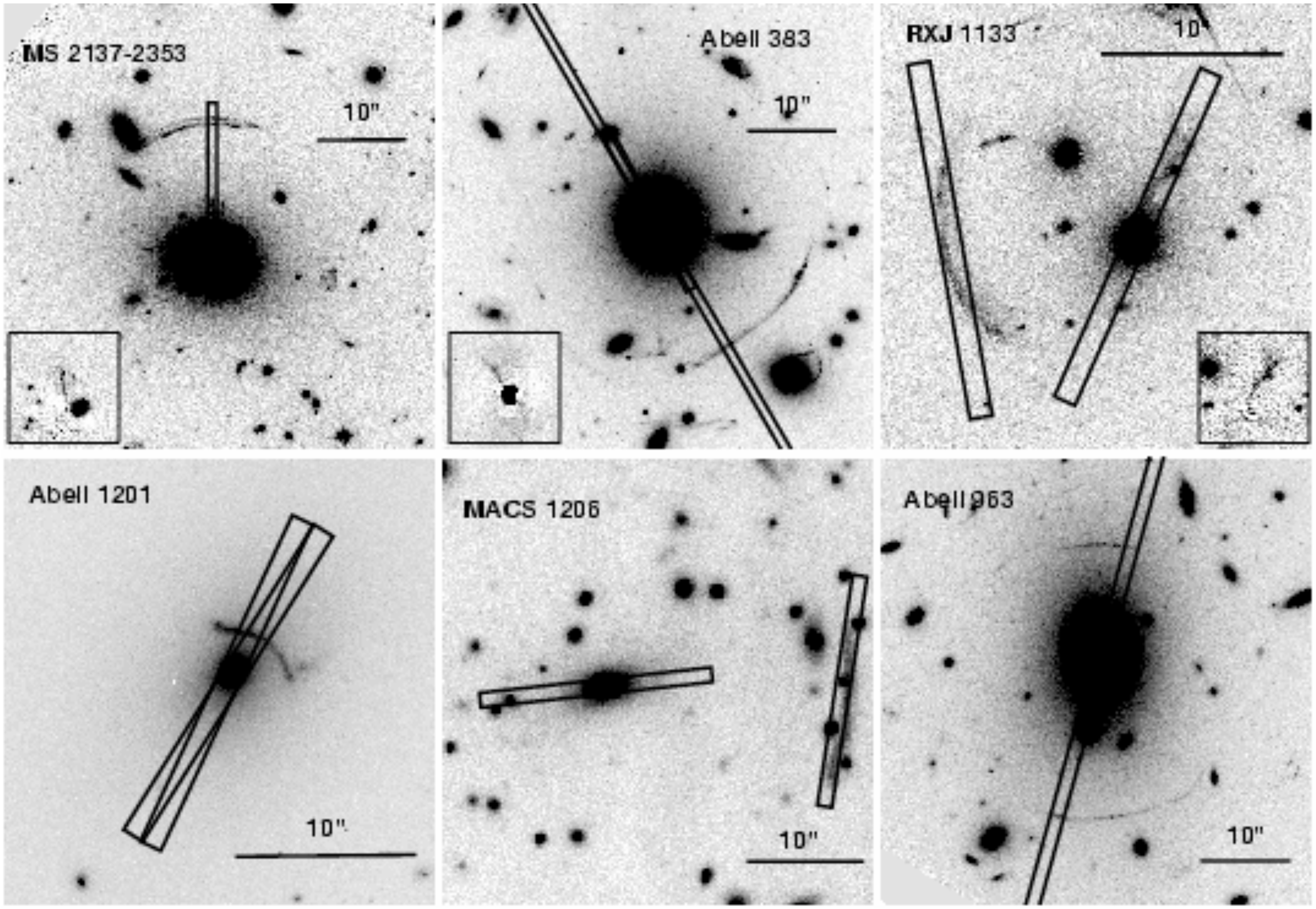


Origin of tangential and radial arcs

Best-fitting density profile for MS2137-23



Keck and Hubble Studies of Arcs

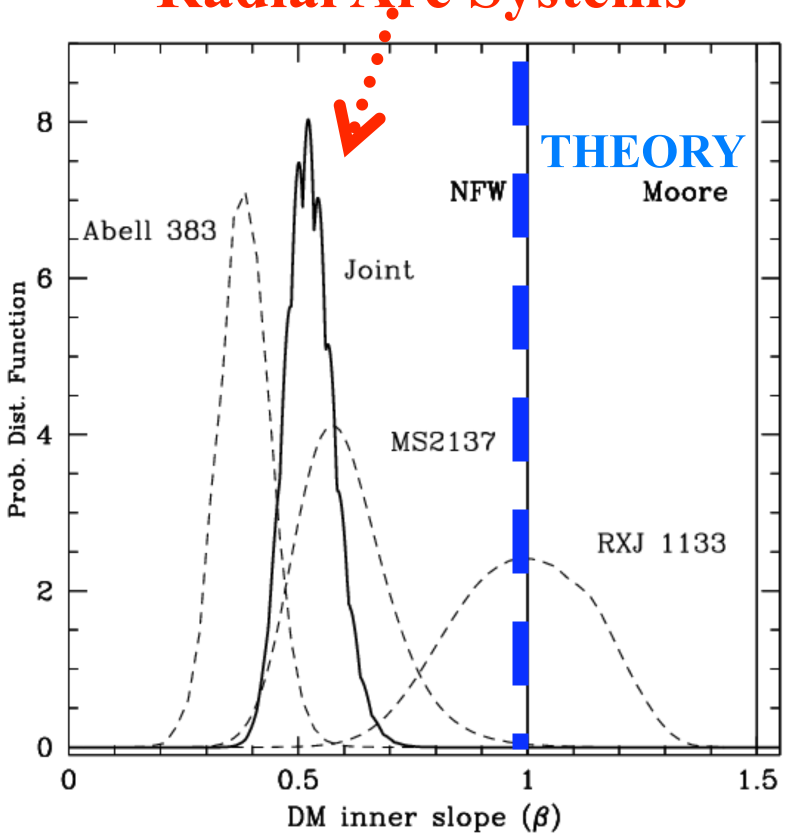


6 systems: 3 with radial arcs, 3 with tangential arcs (control)

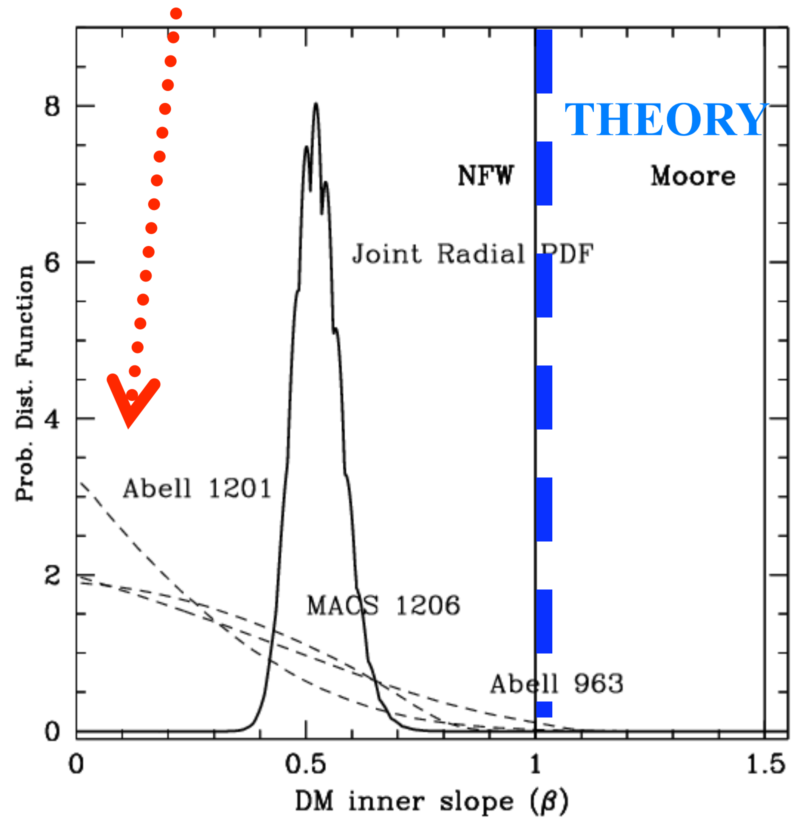
Each studied using combined dynamics and lensing method

Results: Dark Matter Profiles

Radial Arc Systems

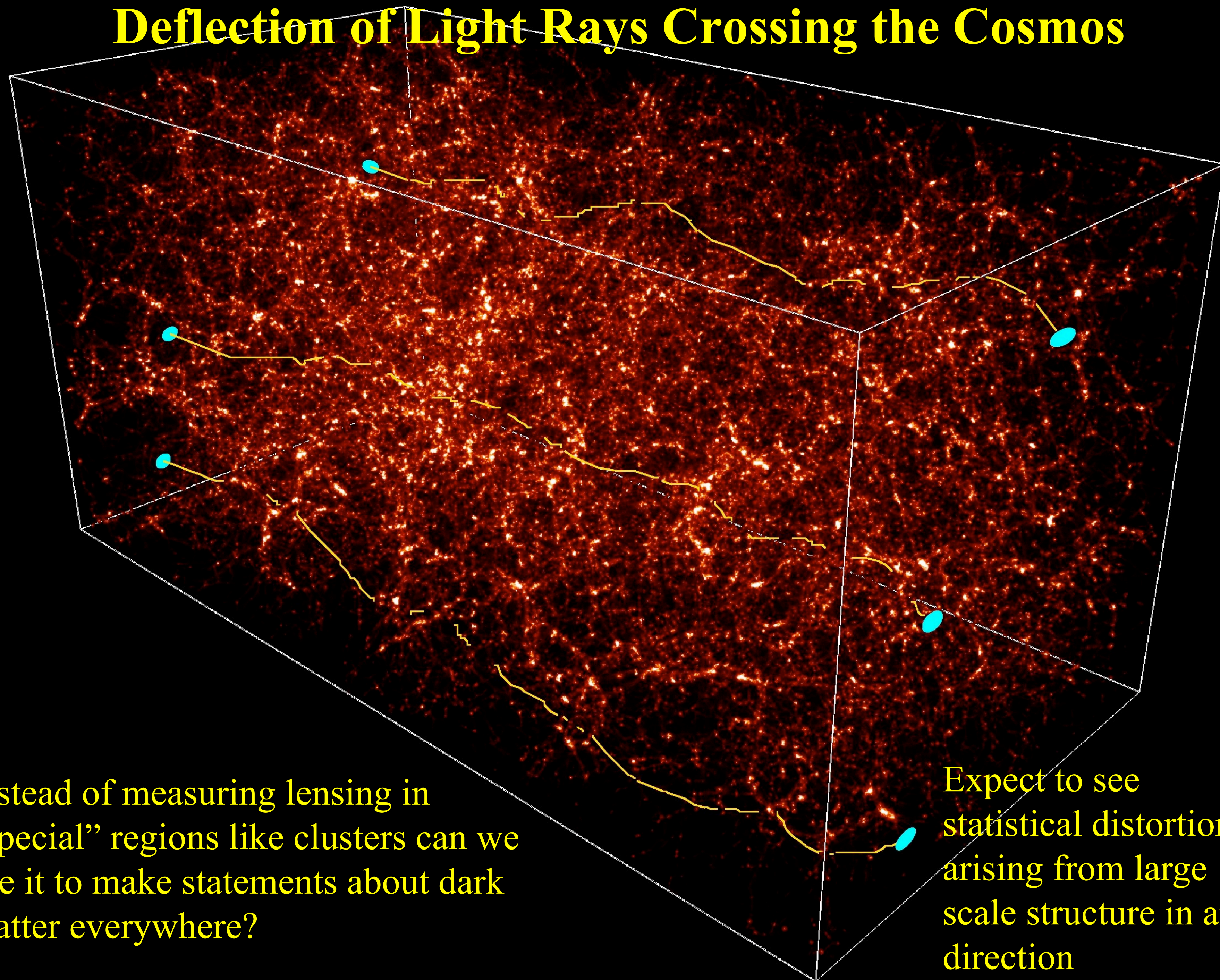


Tangential Arc Systems



Observations reveal that dark matter is less sharply clumped (inner slope β is flatter) than predicted in numerical simulations based on cold (non-interacting) dark matter:

Deflection of Light Rays Crossing the Cosmos



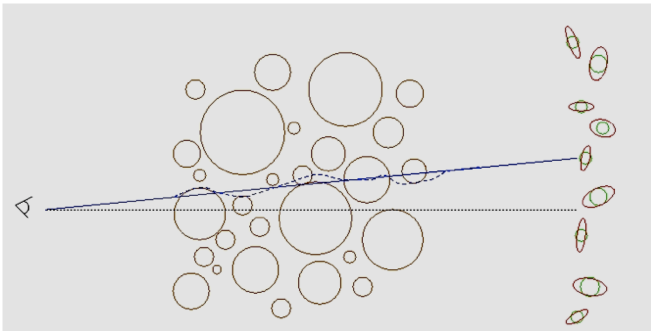
Instead of measuring lensing in "special" regions like clusters can we use it to make statements about dark matter everywhere?

Expect to see statistical distortions arising from large scale structure in any direction

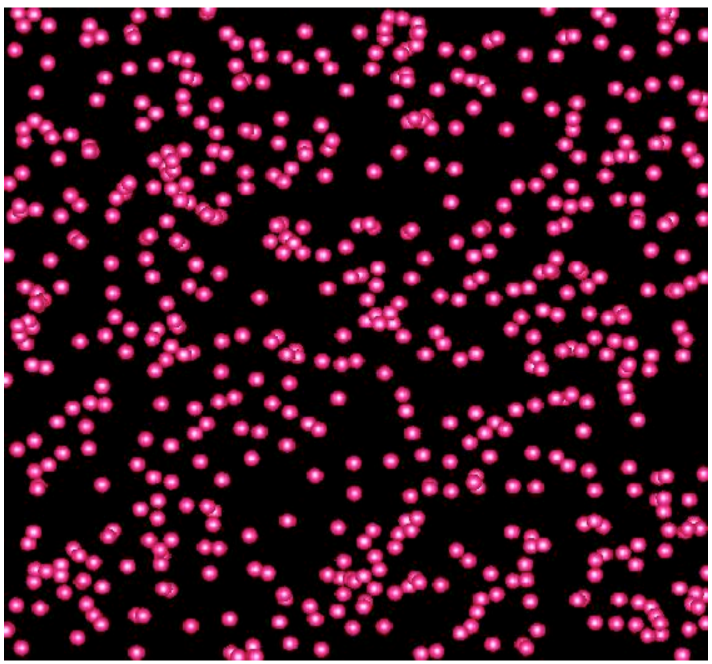
SIMULATION: COURTESY NIC GROUP, S. COLOMBI, IAP.

Weak Lensing

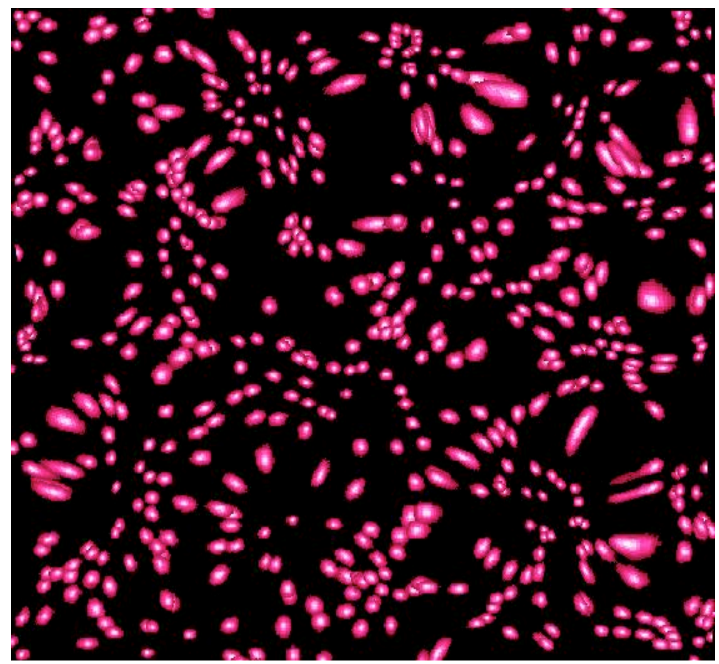
Distortion of background images by foreground matter



Intervening dark matter distorts the shapes of background galaxies

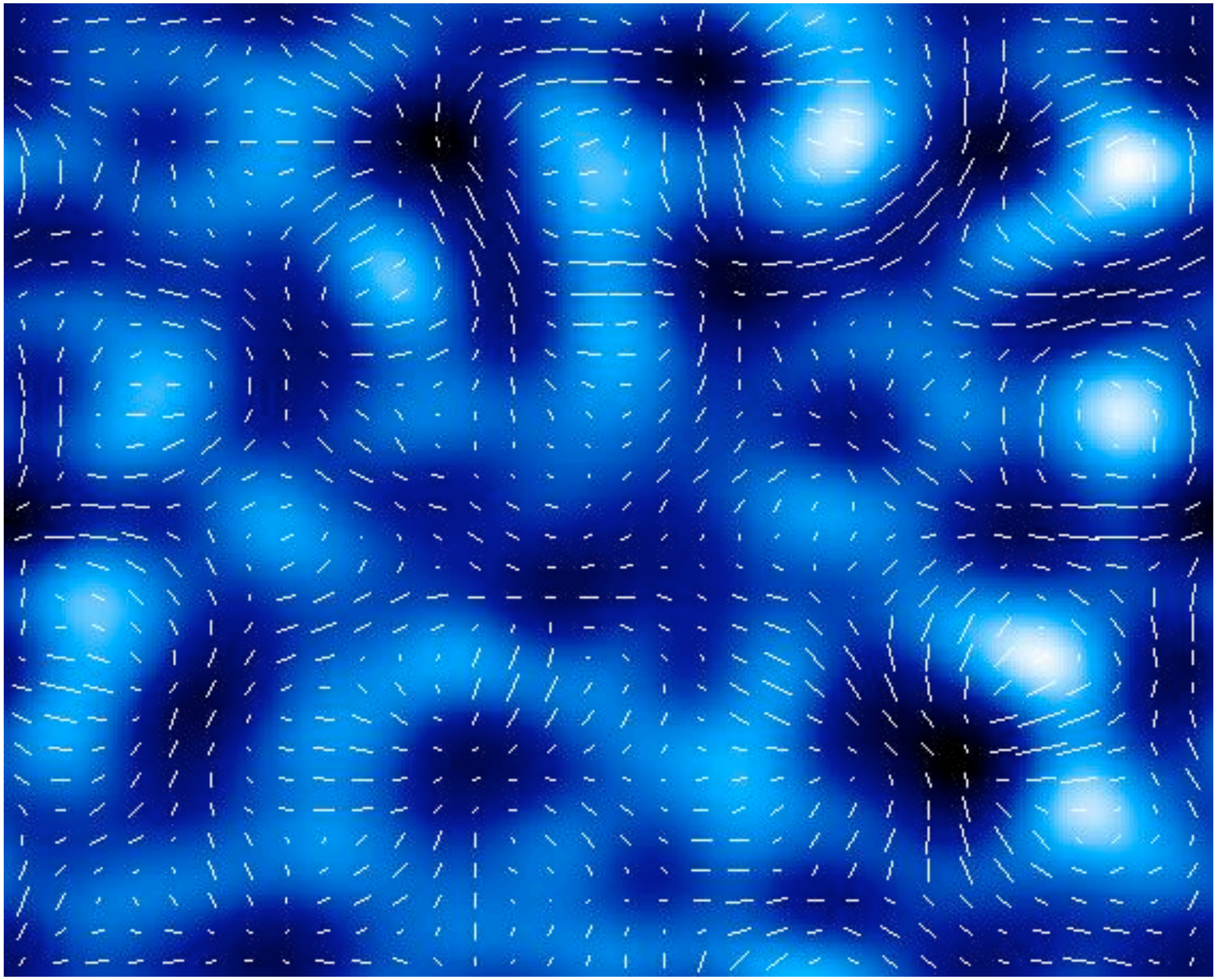


Unlensed



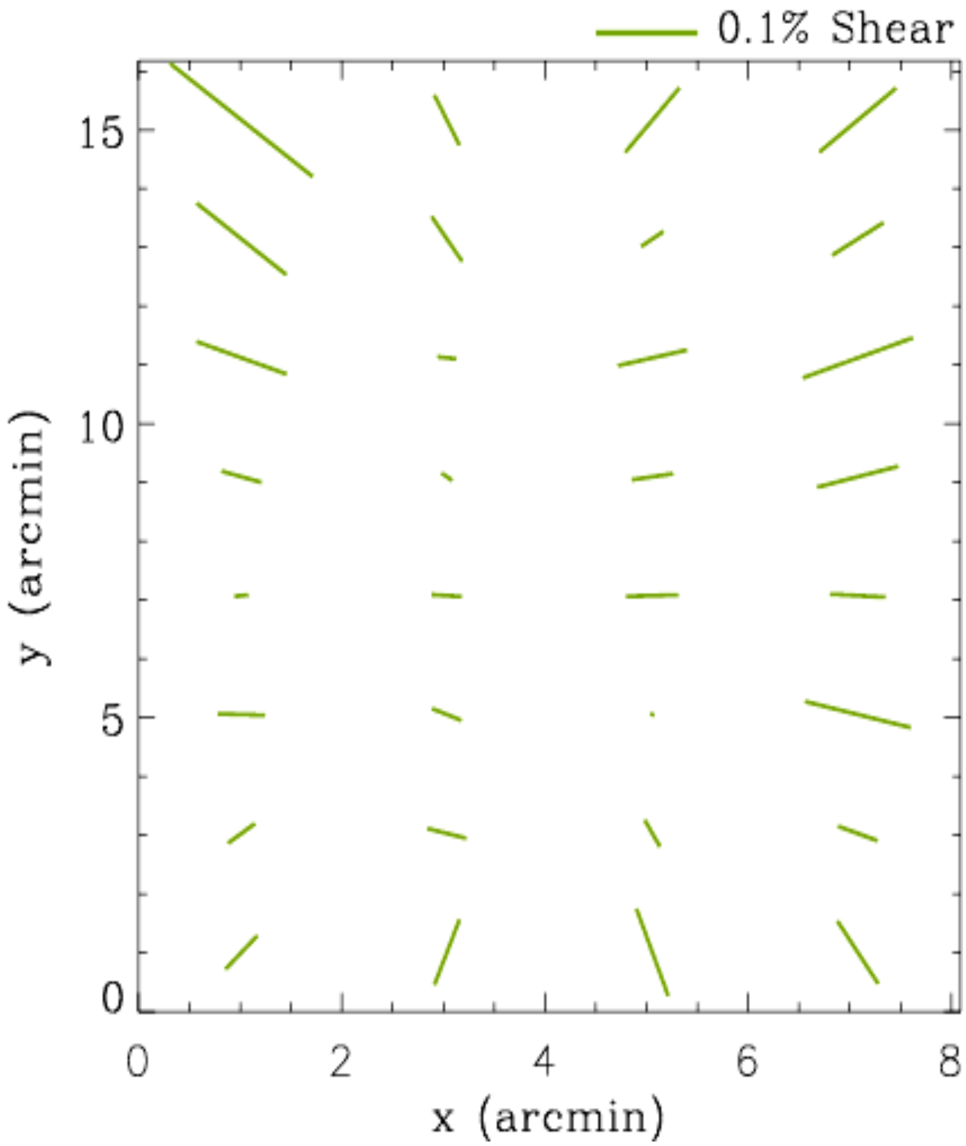
Lensed

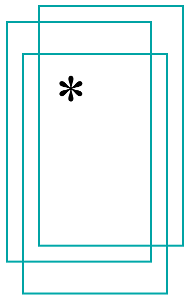
Shear and Mass Density



`Shear' inferred from mean ellipticity of background galaxies in a given direction is used to give the convergence κ – projected mass density along the line of sight

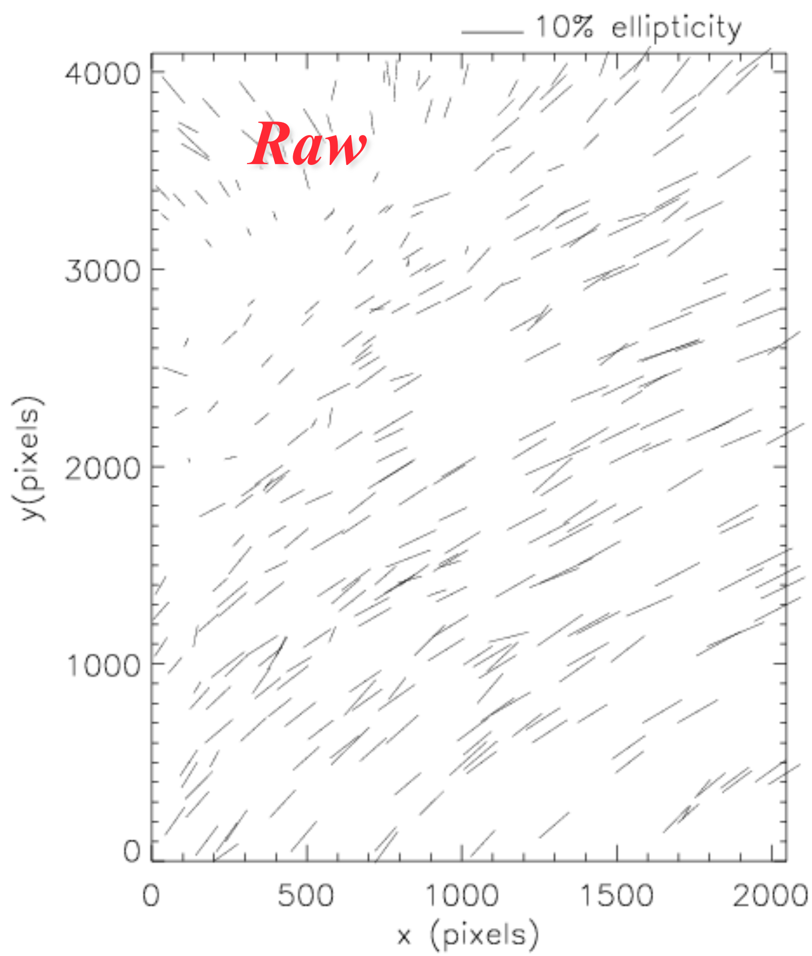
Problems: Camera Distortion

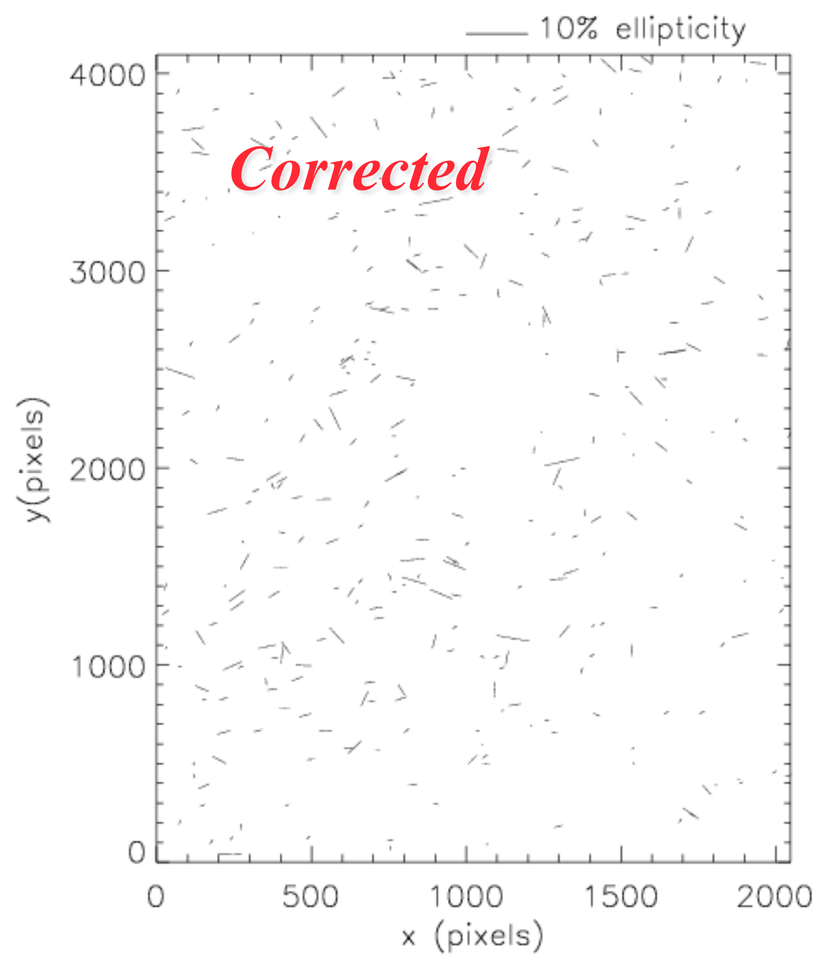




Dithered fields

Problems: Telescope Tracking

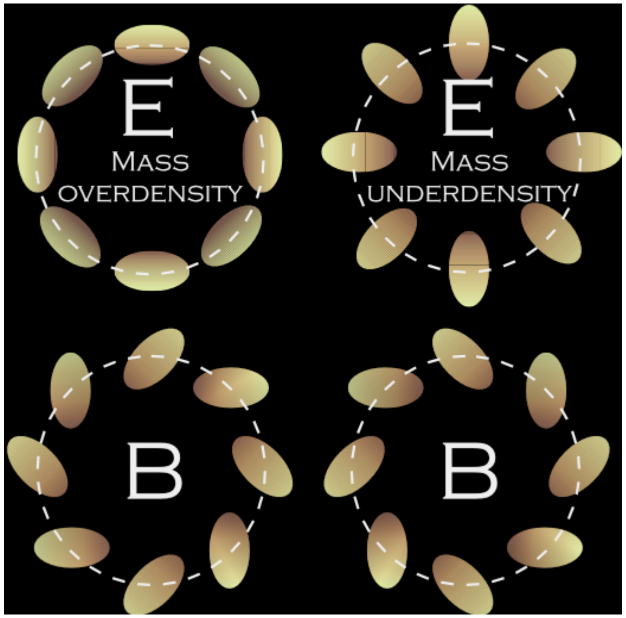


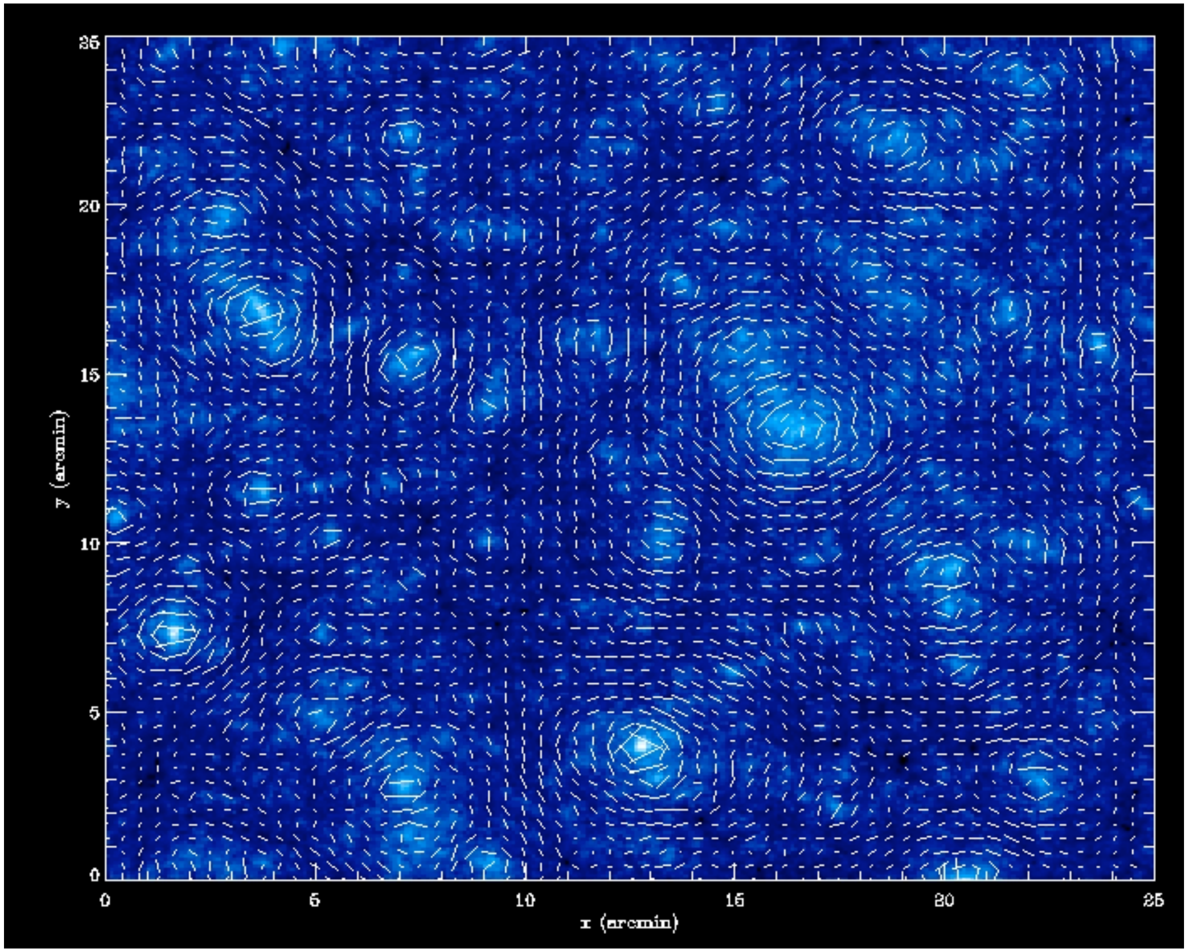


At the level required, even stars are not round on best telescopes!

Raw ellipticities: 3-10% reduced to ~ 0.1% by fitting stellar data

Checking for systematics…





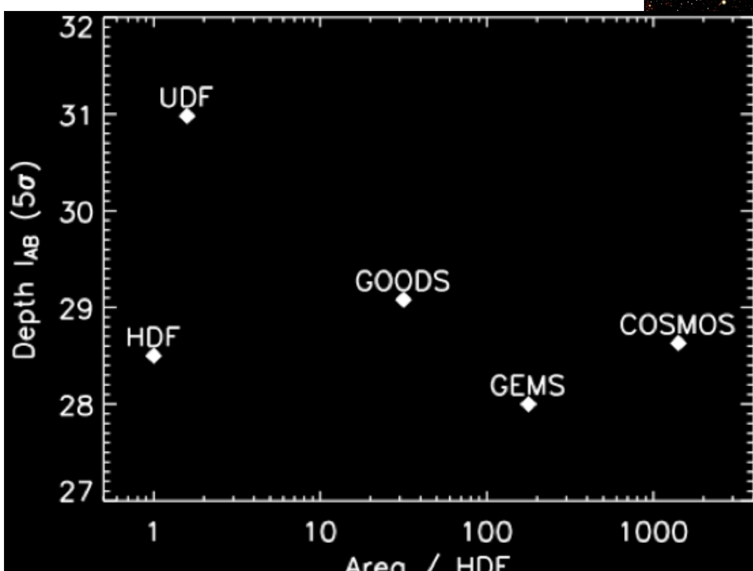
A gravitational lensing signal only produces `E-modes'
Would not expect significant `B-mode' signal

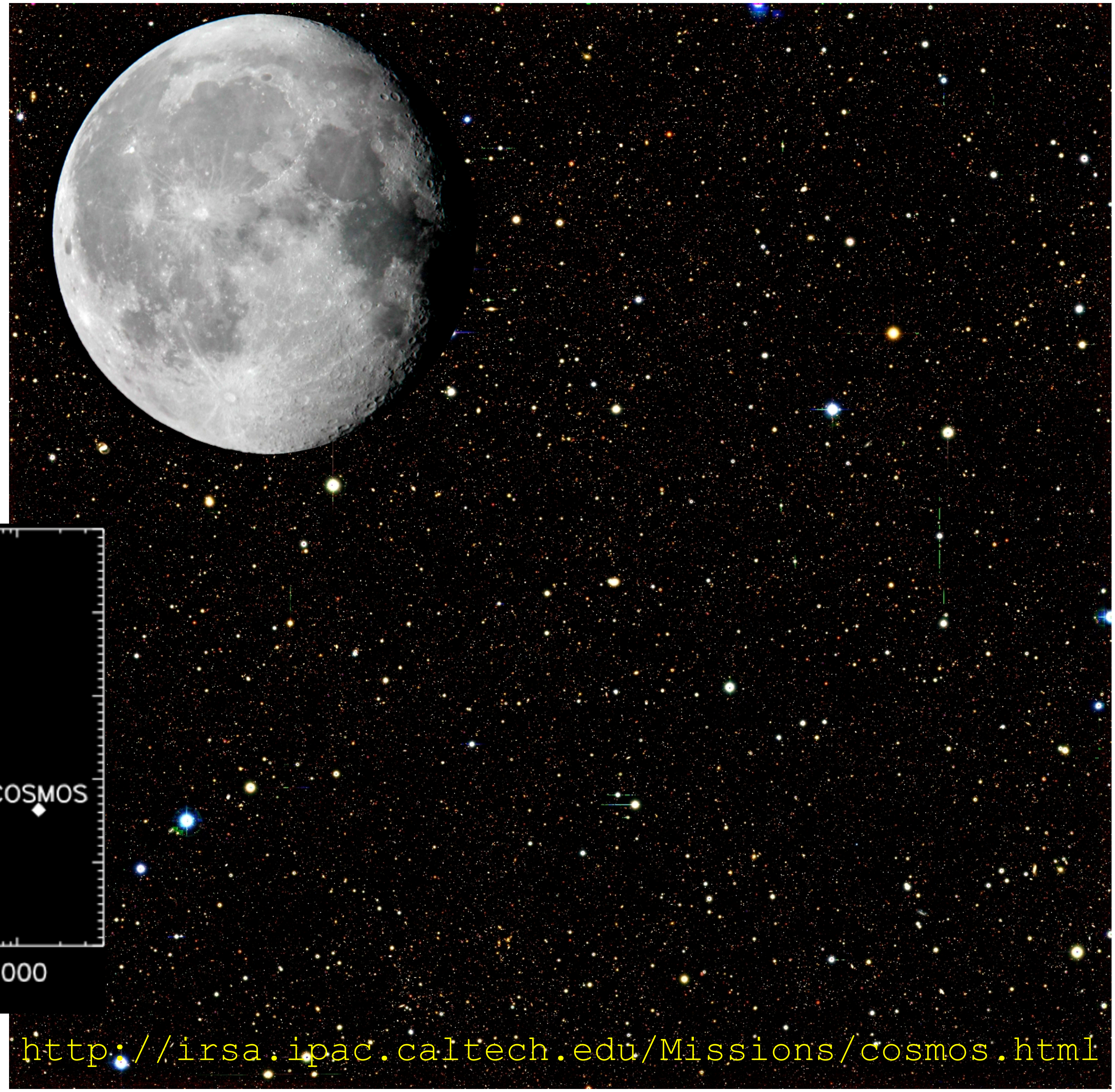
Hubble "Cosmic Evolution Survey"

COSMOS:

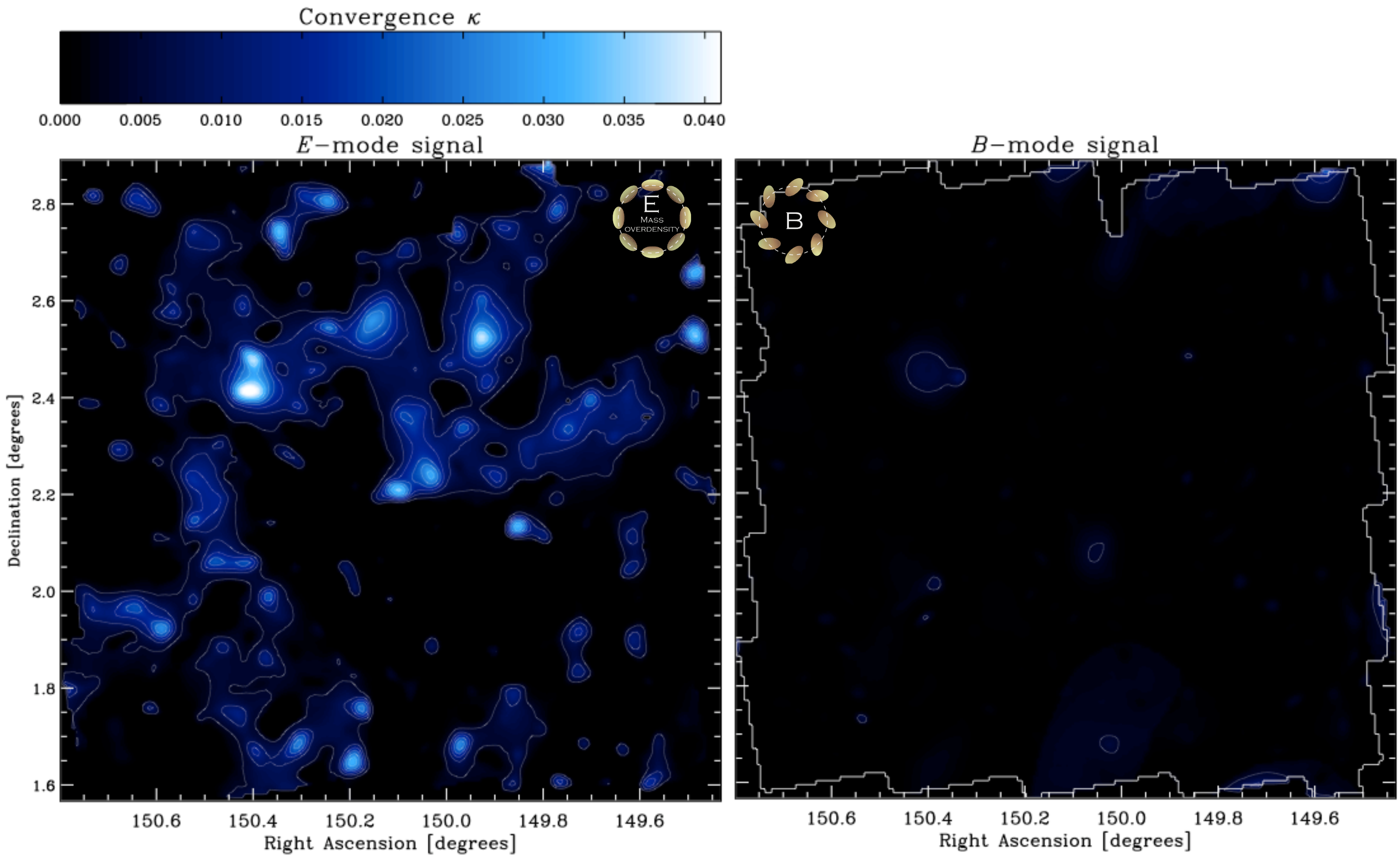
Largest HST survey

- 587 ACS fields
- 2 deg^2 in F814W
- F814W<26.6 (5σ)
- 2. 10^6 galaxies
- ~80 resolved $arcmin^{-2}$

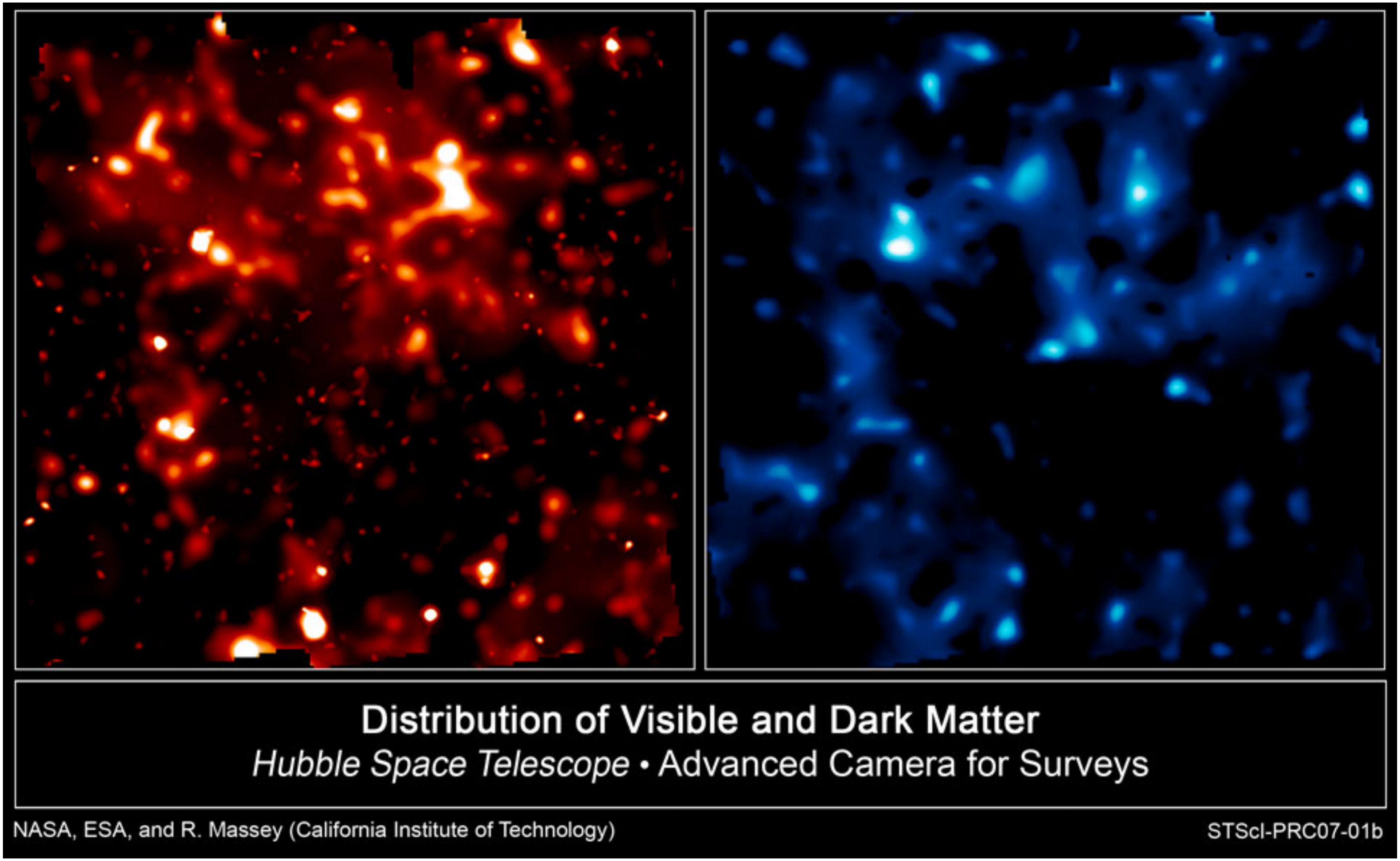




Dark Matter Map: E- and B-modes

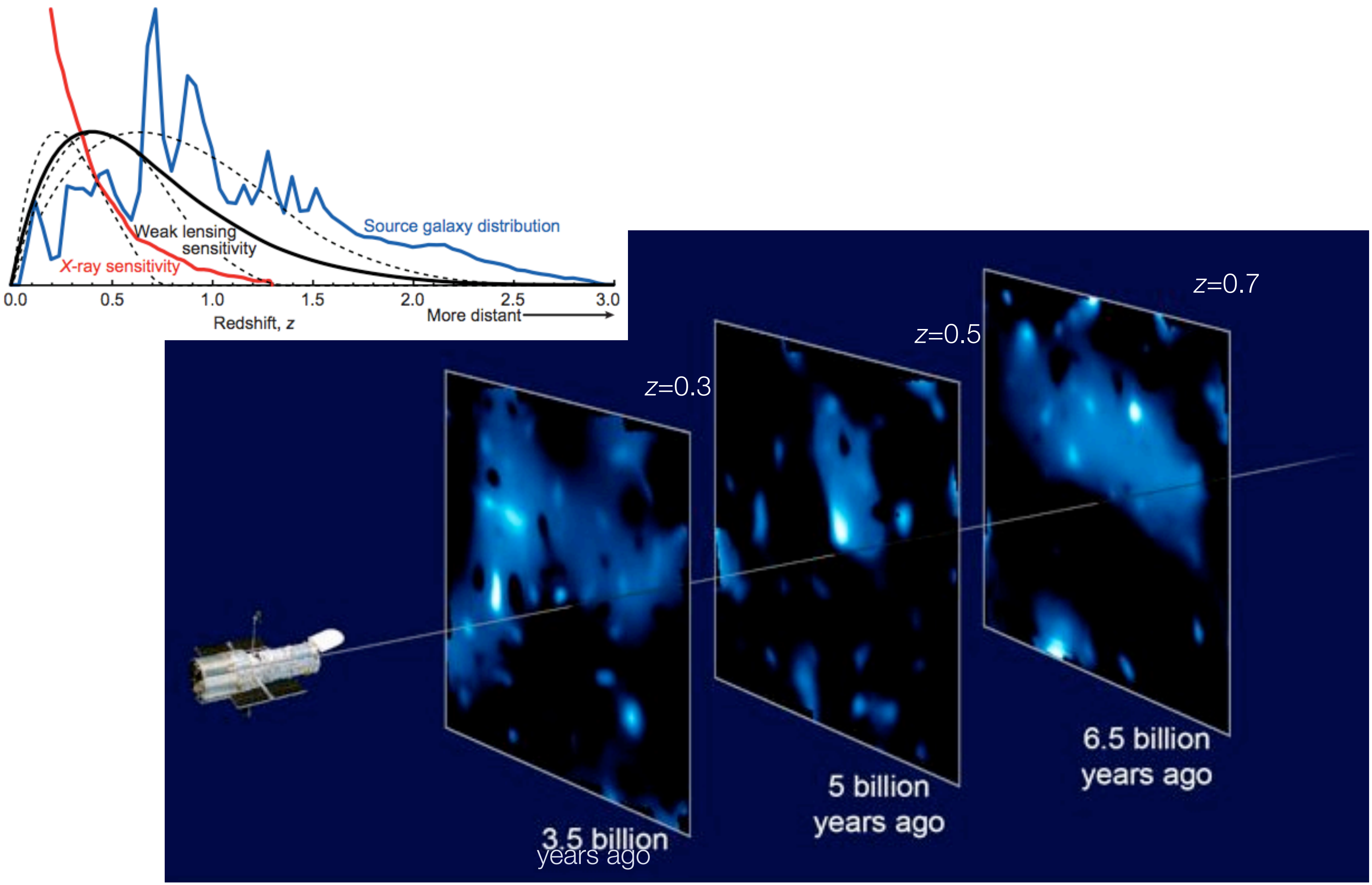


Comparing Light and Dark Matter

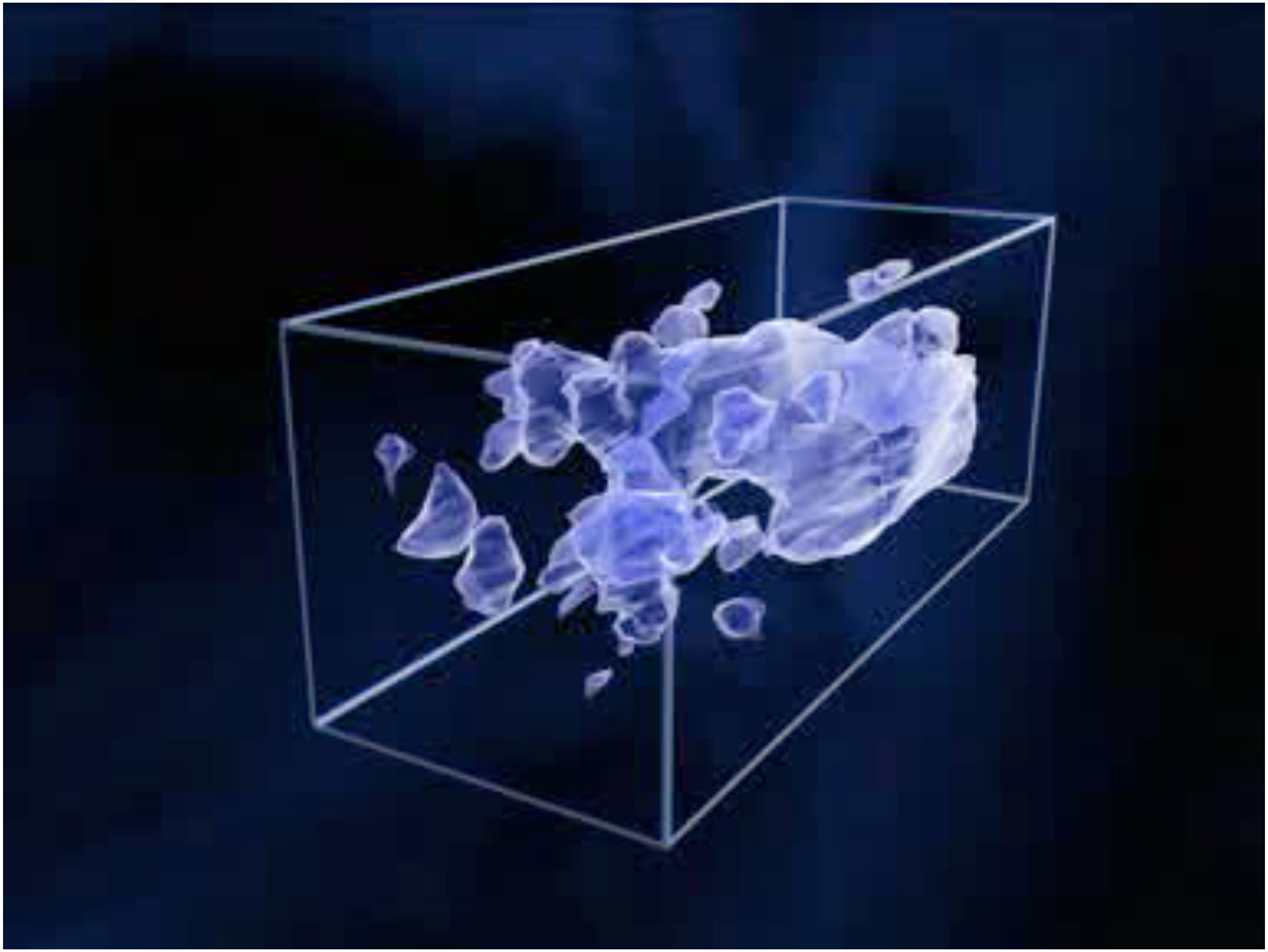


Massey et al Nature 445, 286 (2006)

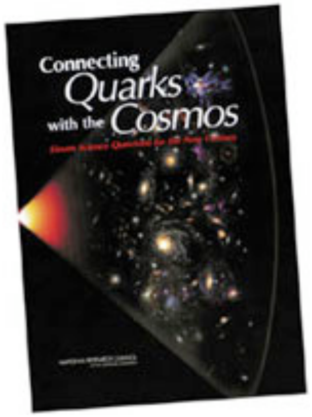
Growth of Dark Matter Clustering



3D Distribution of Dark Matter



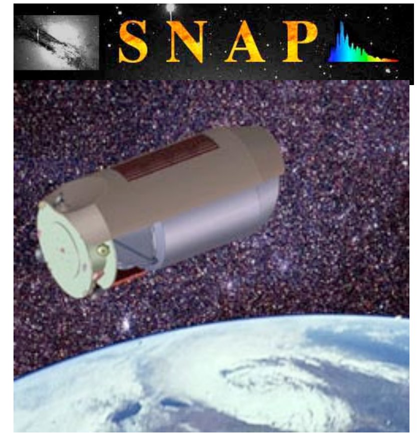
New Proposals for Tracking Dark Energy



NASA initiates studies for a Dark Energy mission (WFIRST)

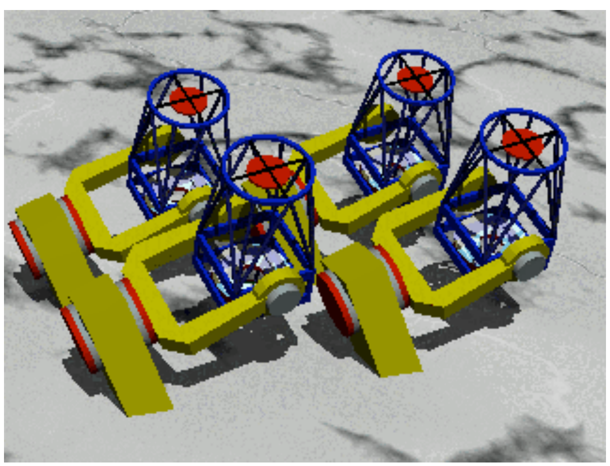
ESA does likewise with Euclid

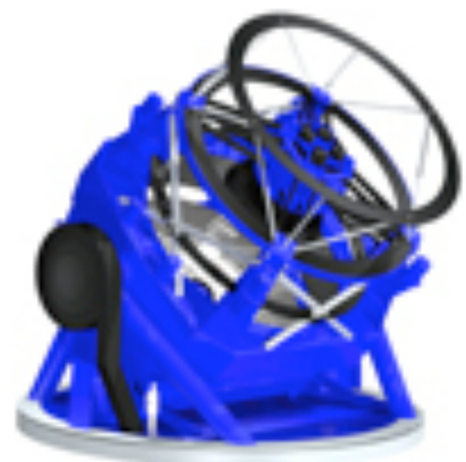
Possible ESA/NASA merger?



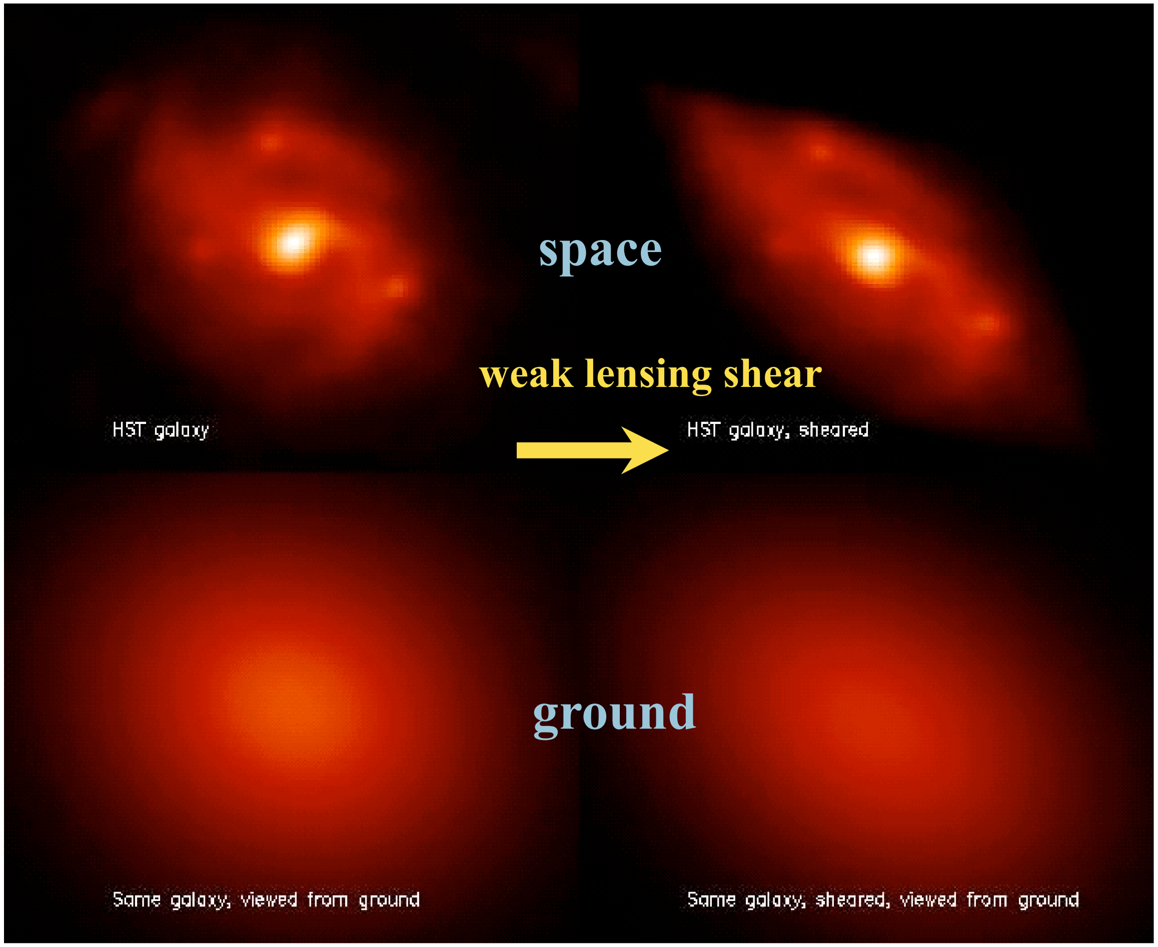
Shorter term initiatives on the ground (DoD/DoE/NSF):

Pan-STARRS (2009) Dark Energy Survey (2012), VISTA-Dark Camera (2011), Subaru HSC/WFMOS (2011-), LSST (2017+)





Ground versus Space



Typical cosmic shear is ~ 1%, and must be measured with high accuracy

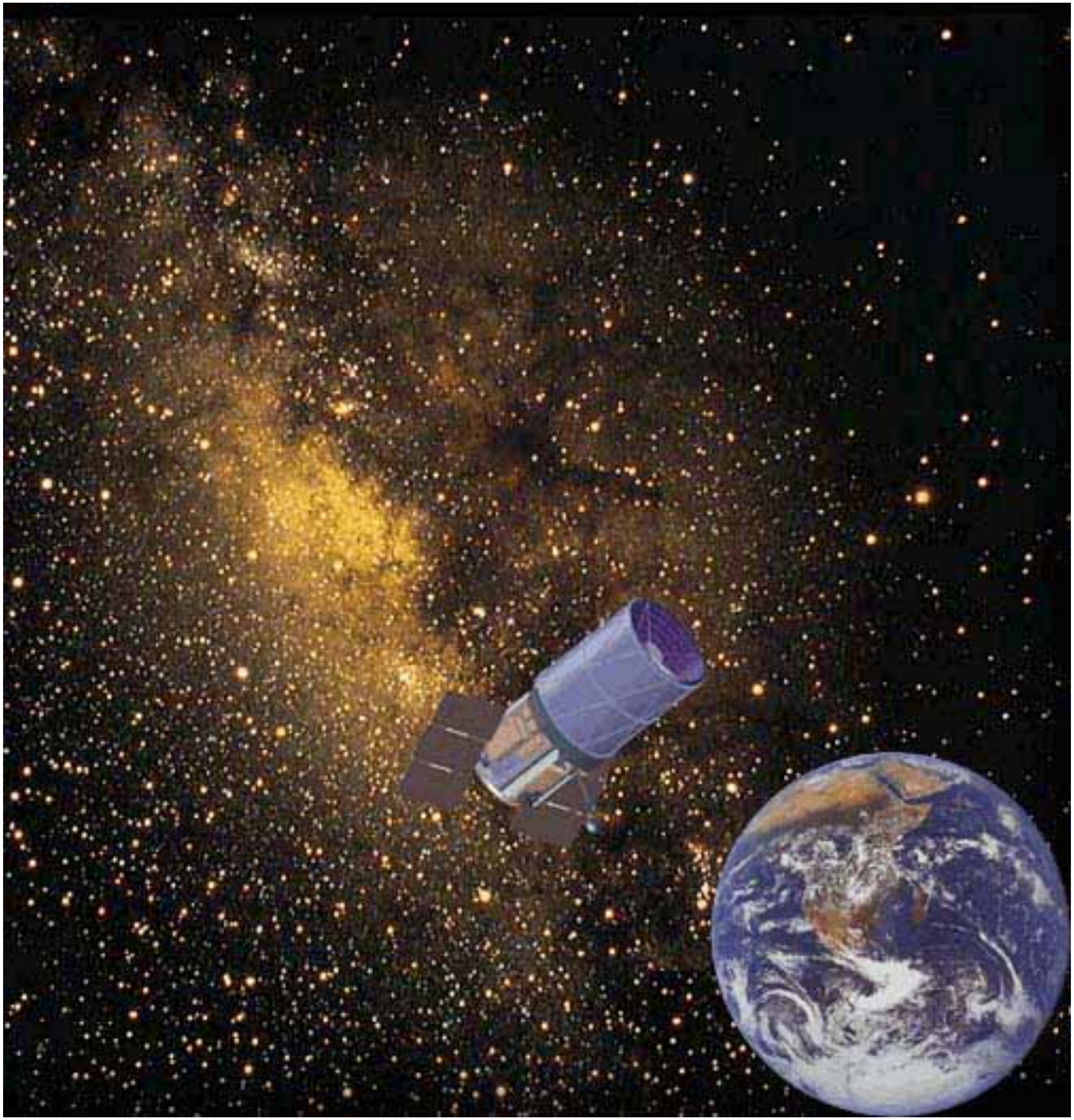
Space: small and stable PSF:

⇒ larger number of resolved galaxies

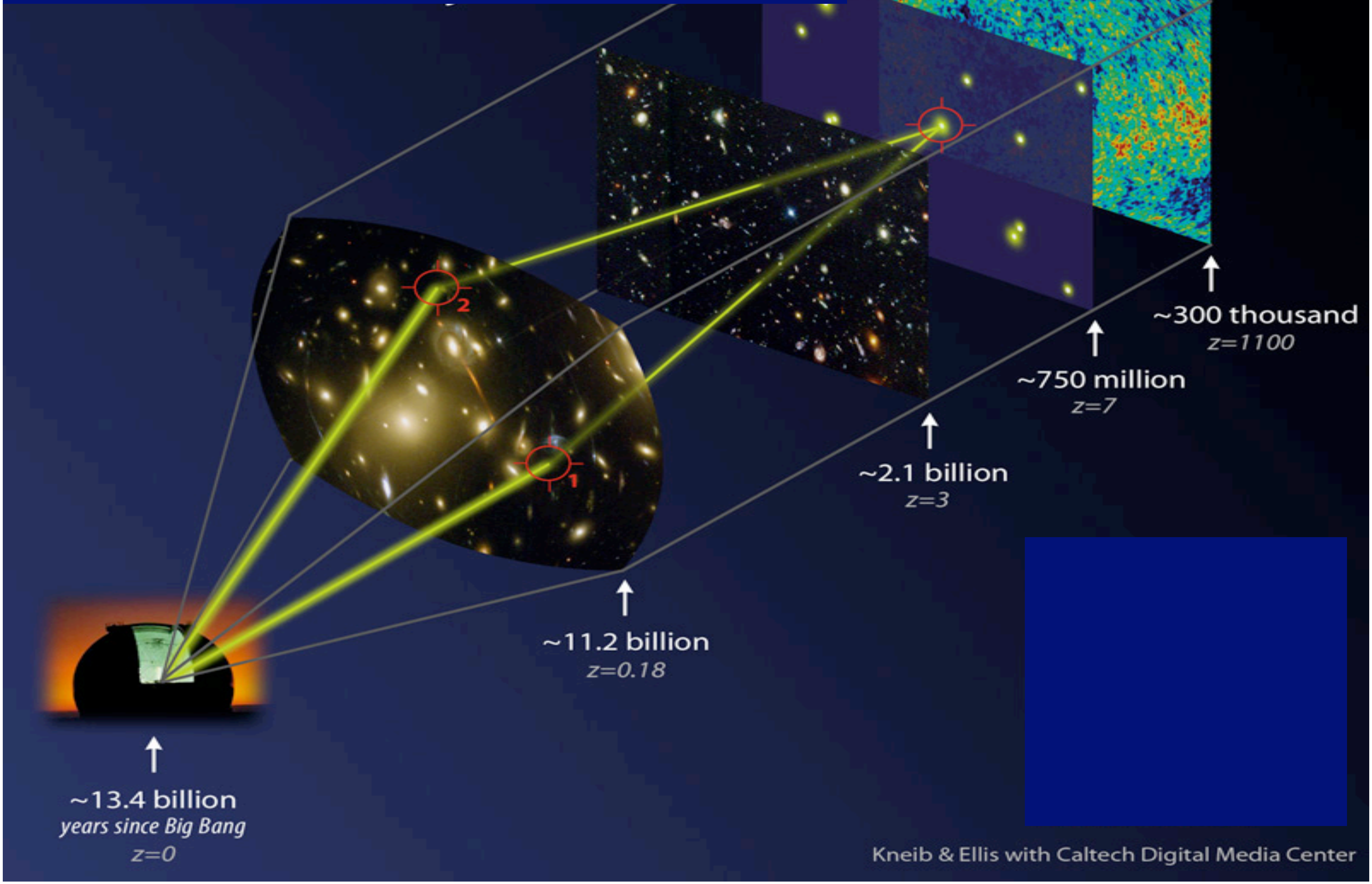
⇒ reduced systematics

Wide field Infrared Space Telescope (WFIRST)

A new wide-field space telescope which would extend the Hubble results by directly mapping dark matter at various cosmic times: this would trace **dark energy**

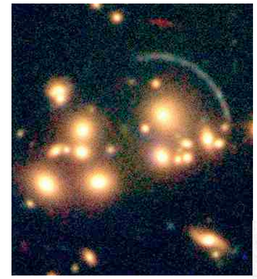
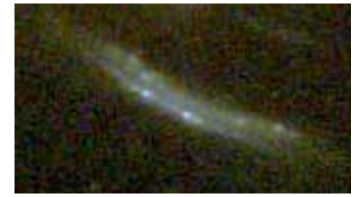
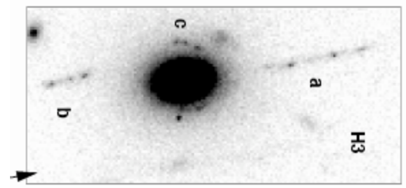
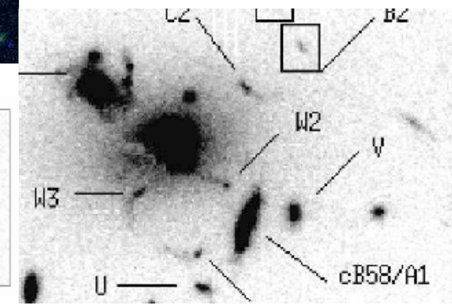


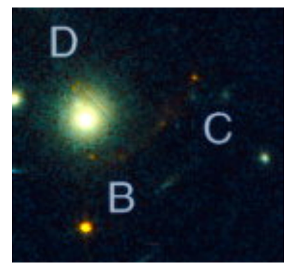
Exploring the very early Universe

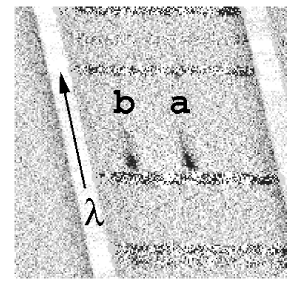


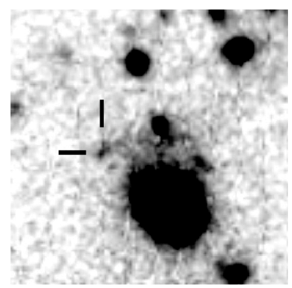
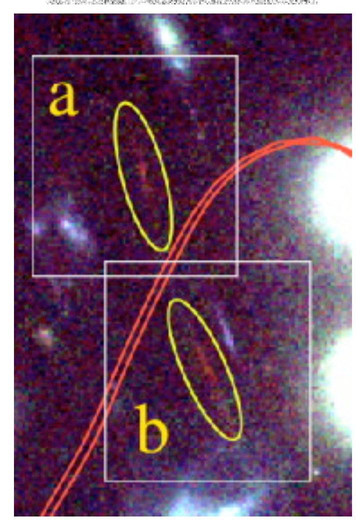
Gravitationally Lensed Galaxies: Record Breakers (1991-2008)

- Abell 370 (z=0.724); Soucail et al 1988
- Cl2244-02 (z=2.237); Mellier et al 1991
- A2218 #384 (z=2.515); Ebbels et al 1996
- MS1512 cB58 (z=2.72); *Yee et al 1996*, Seitz et al 1998
- A2390 (z=4.05); Frye et al 1998, Pellò et al 1999
- MS1358+62 (z=4.92); Franx et al 1997
- A2218 (z=5.7); Ellis et al 2001
- A370 (z=6.56); Hu et al 2002
- ***A2218 (z~6.8); Kneib et al 2005***
- ***A1689 (z~7.6); Bradley et al 2008***

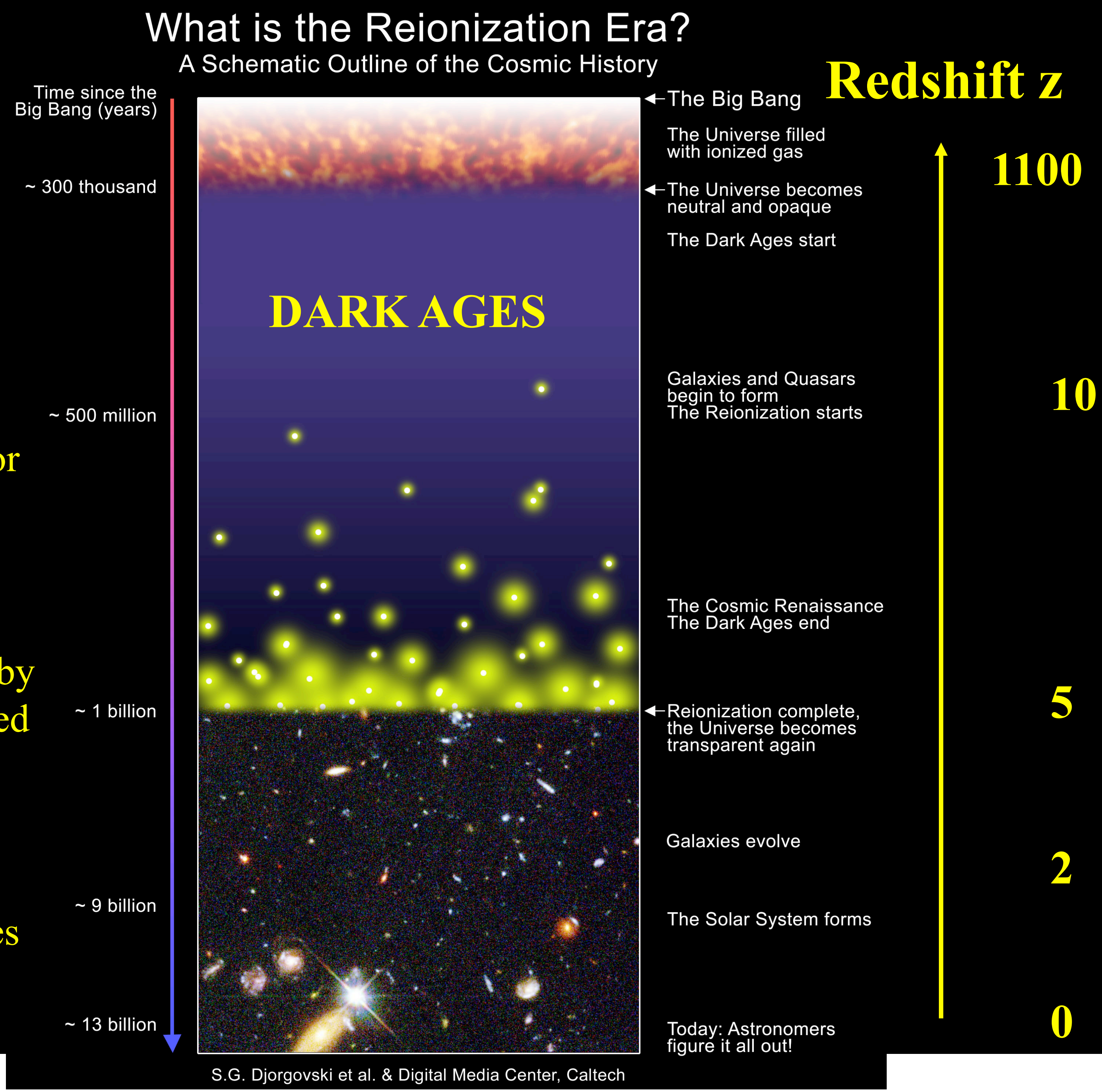









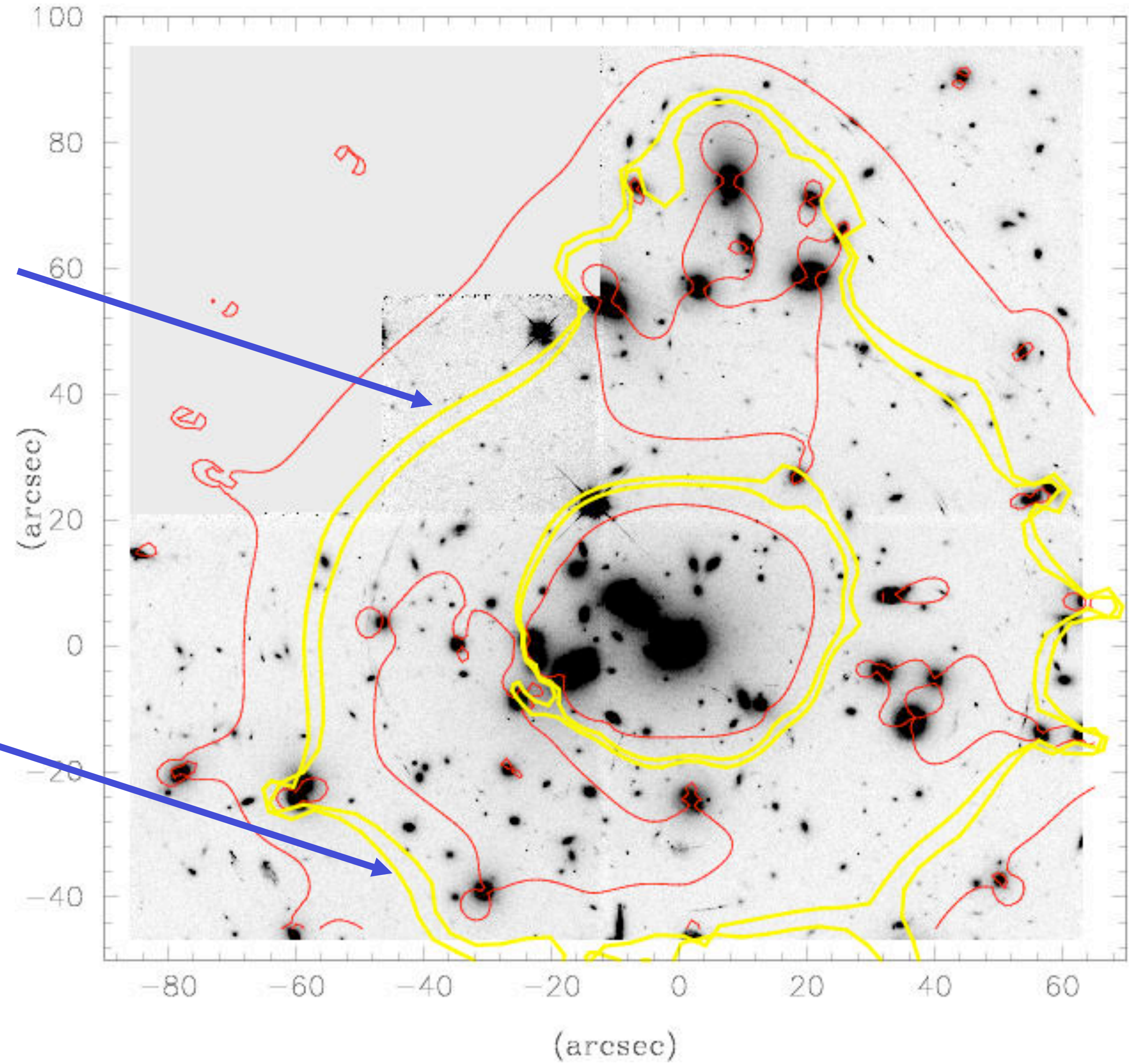
- After the microwave background the Universe enters the so-called “dark ages” prior to formation of first stars
- Hydrogen is then re-ionized by the newly-formed stars
- How do we explore this era when the sources are so faint?



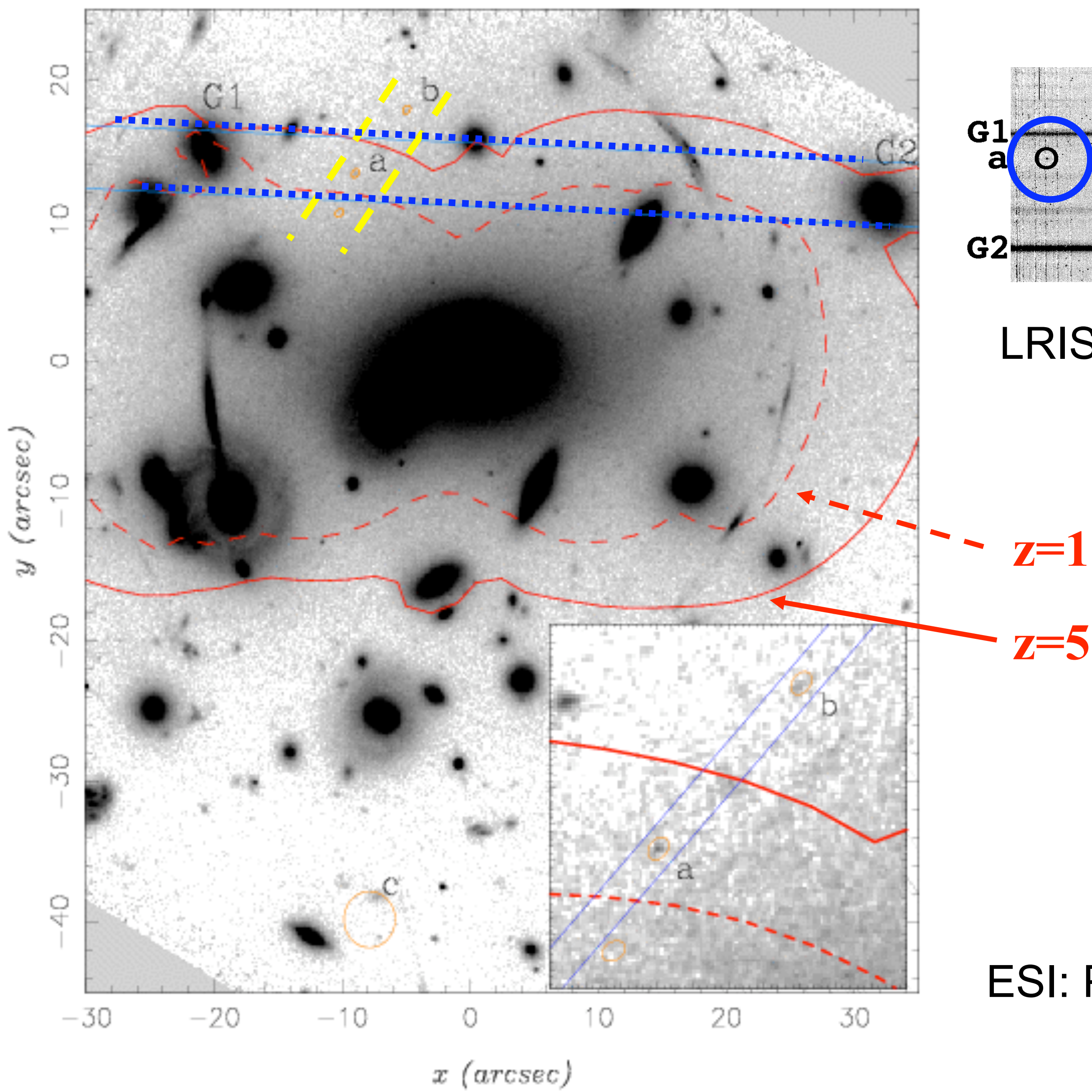
Charting Regions of Maximum Magnification

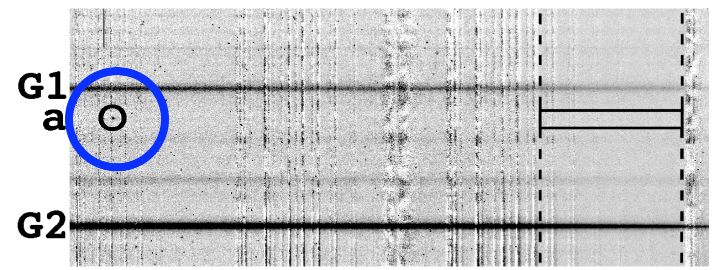
We know precisely which small strips of sky are those where background sources are **highly magnified.**

So we search those areas only for the earliest stars!

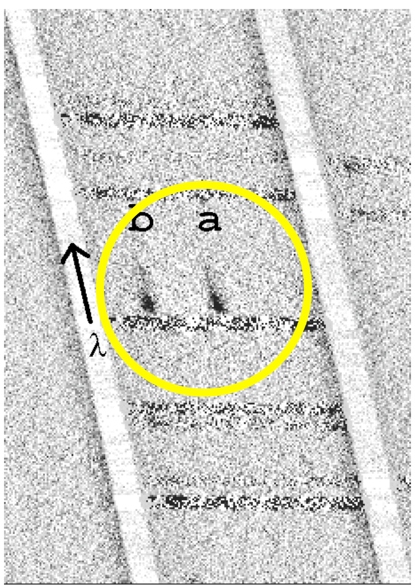


Finding Very Distant Magnified Systems



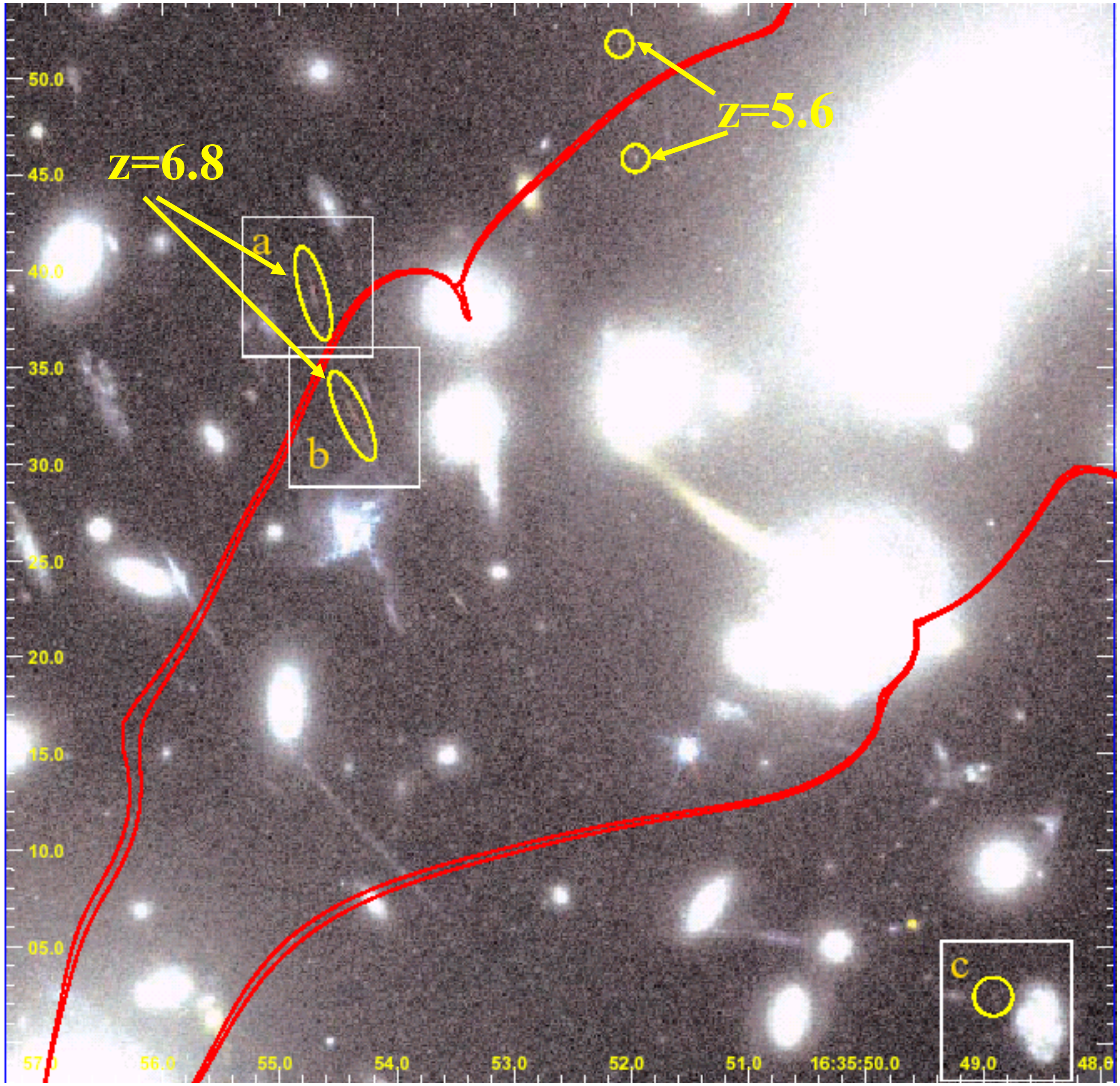


LRIS: Single line detection



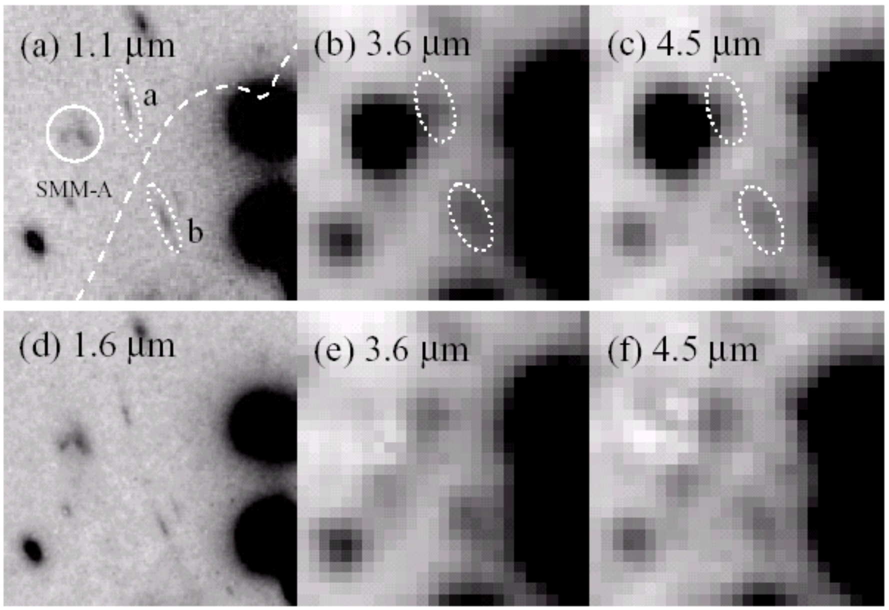
ESI: Pair confirmation

Further examples

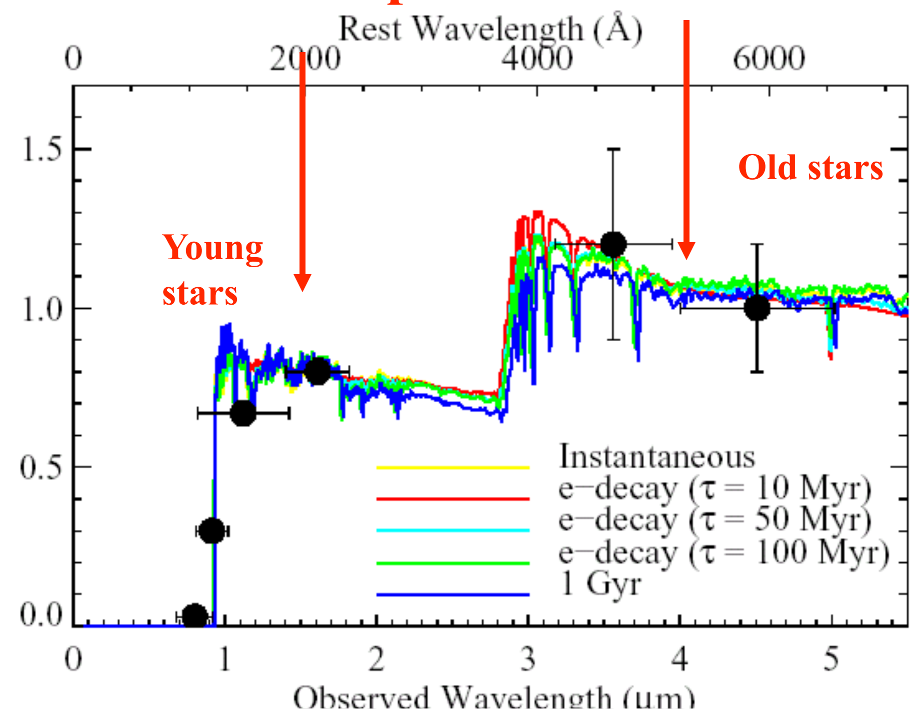


Detailed Study of Multiply-Imaged z~6.8 galaxy

Hubble Spitzer



Hubble Spitzer



Spitzer → this is already a well-established system 800 Myrs after Big Bang

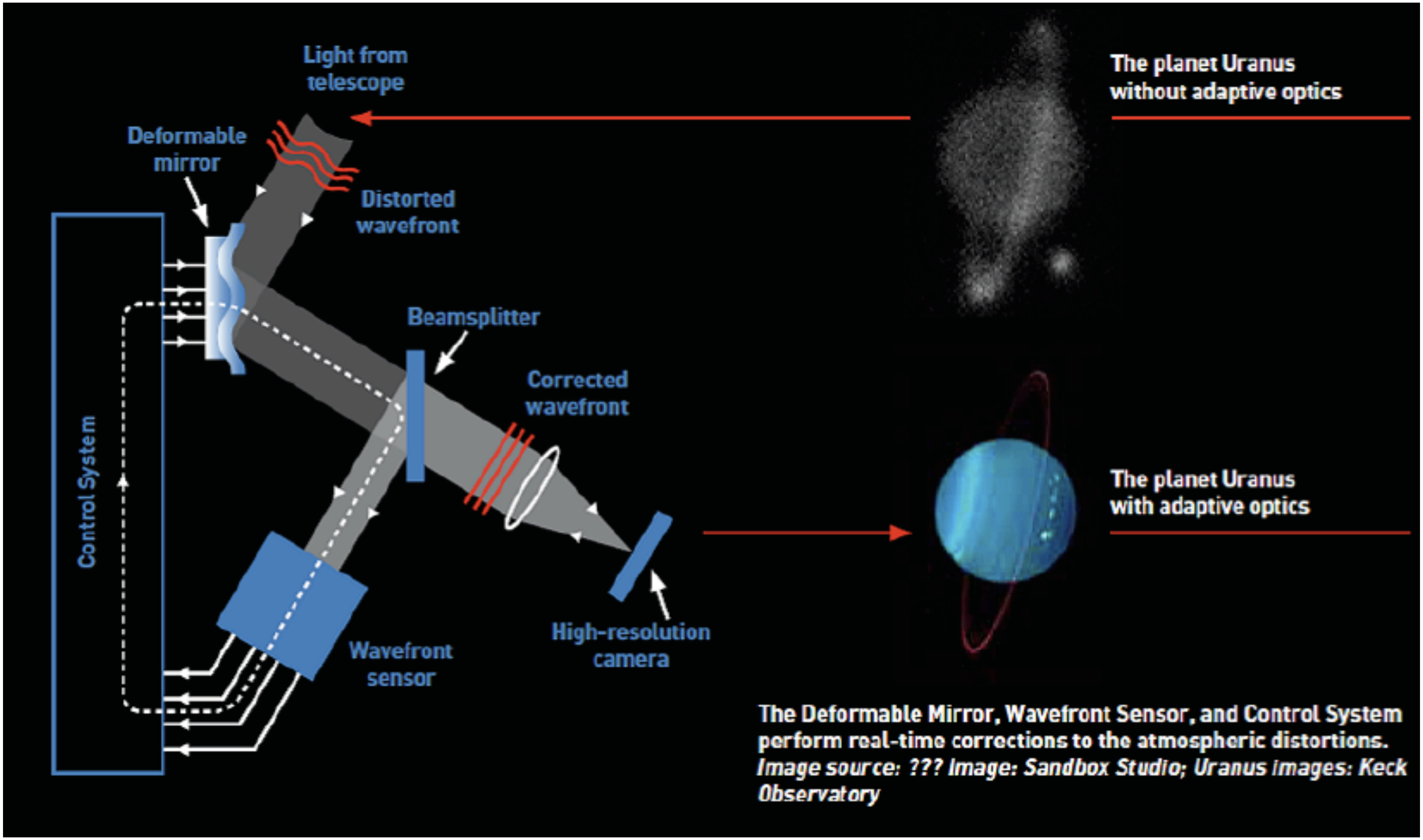
Star formation rate = 2.6 solar masses/yr; stellar mass ~ 0.5% Milky Way

Age at this epoch: 100 – 450 million yrs, so formed at $9 < z_F < 12$

Puzzle: despite heroic exposure with NIRSPEC – did not detect Ly α


All Sky Adaptive Optics is Here!

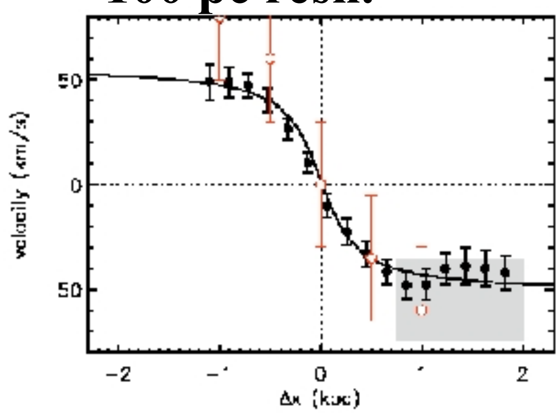
Adaptive Optics: How It Works

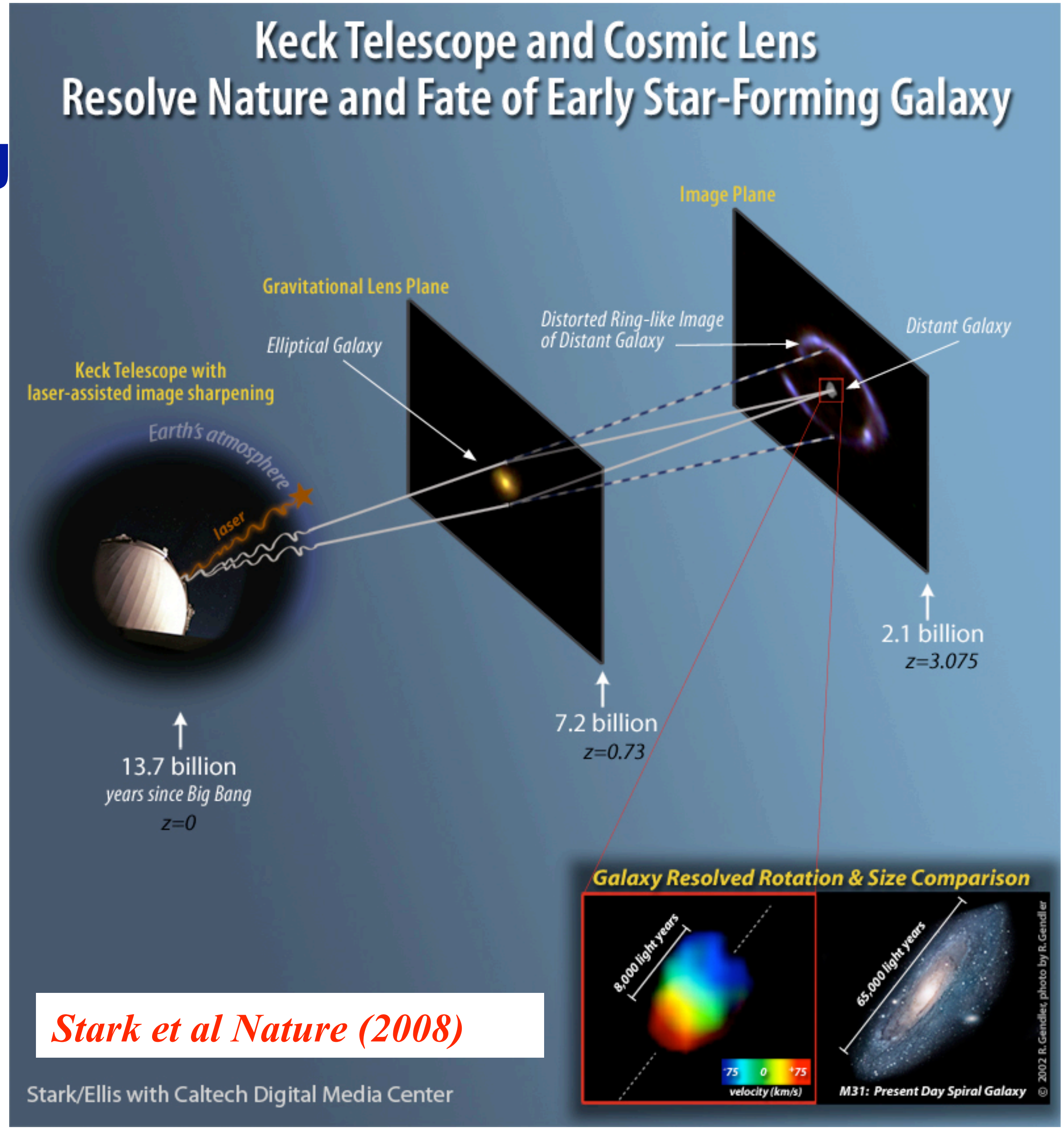


The Deformable Mirror, Wavefront Sensor, and Control System perform real-time corrections to the atmospheric distortions. *Image source: ??? Image: Sandbox Studio; Uranus images: Keck Observatory*

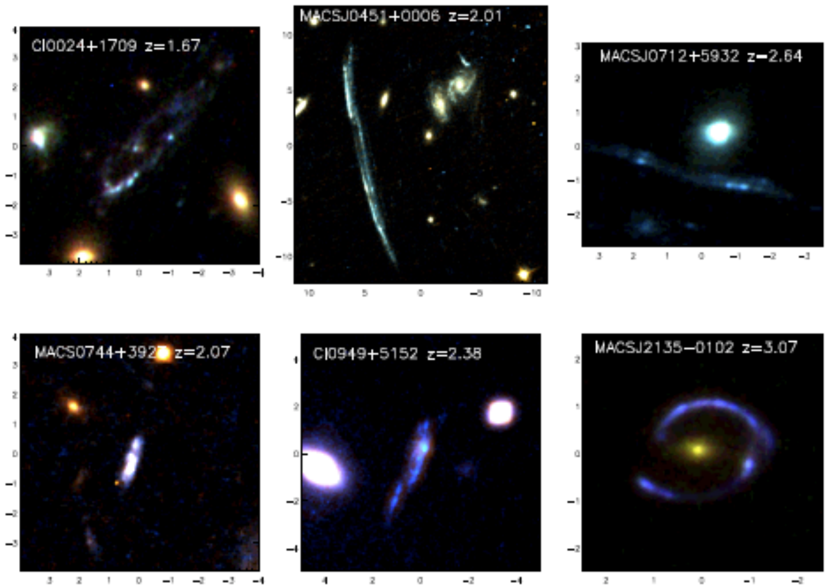
Strong Lensing as a Magnifying Glass

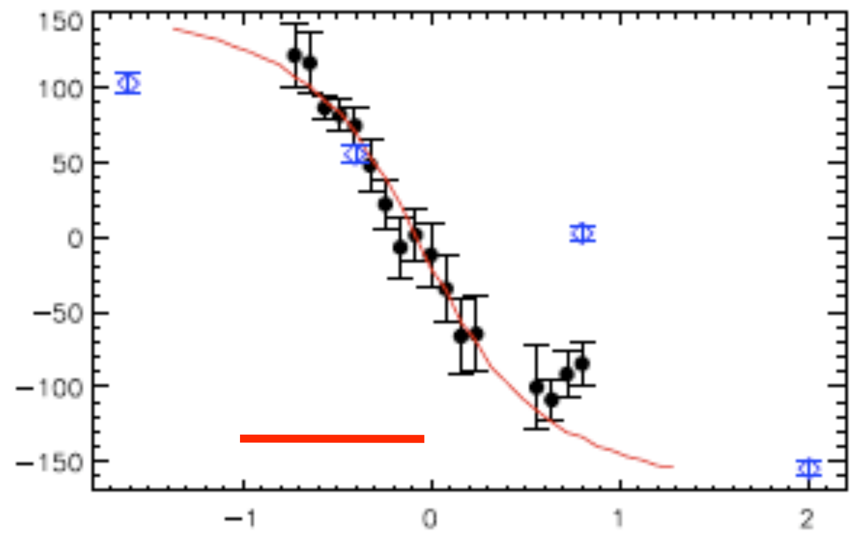
Rotation curve with 100 pc resn.

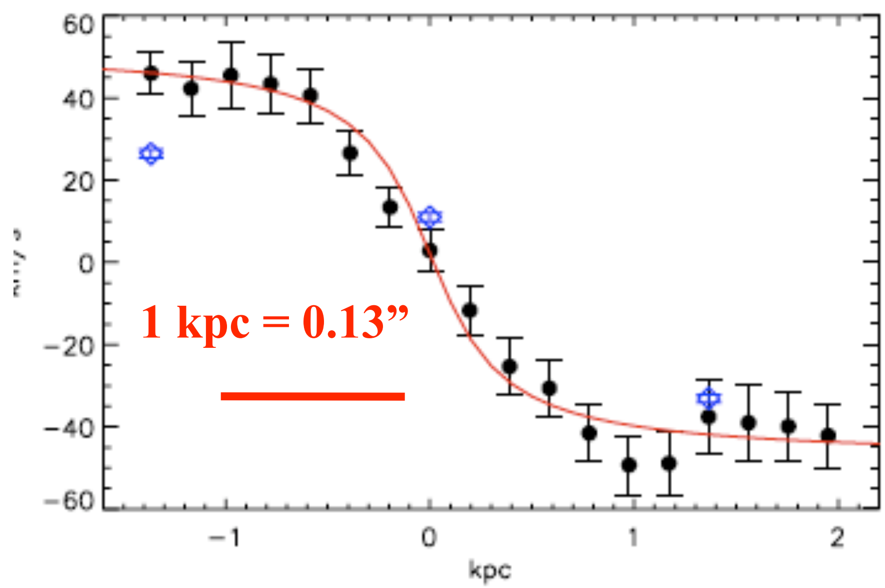




Resolved Dynamics (~100 pc resn!) via Combination of Lensed Magnification and Keck Adaptive Optics





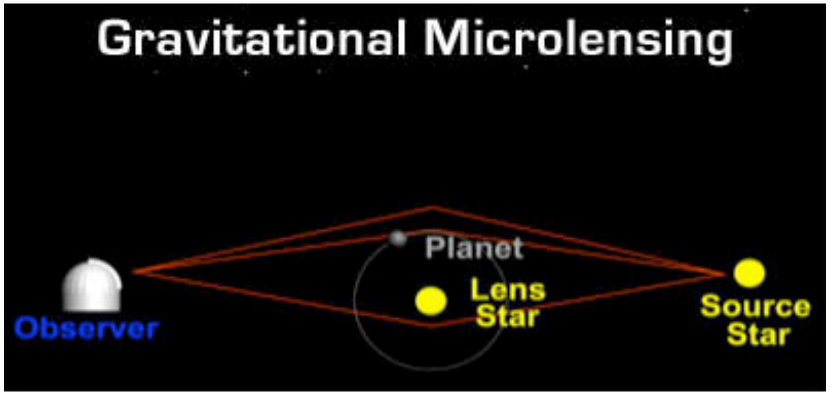


6 lensed galaxies 1.7 < z < 3.1 (linear magnification ~8-10) revealing rotation in 5/6 cases

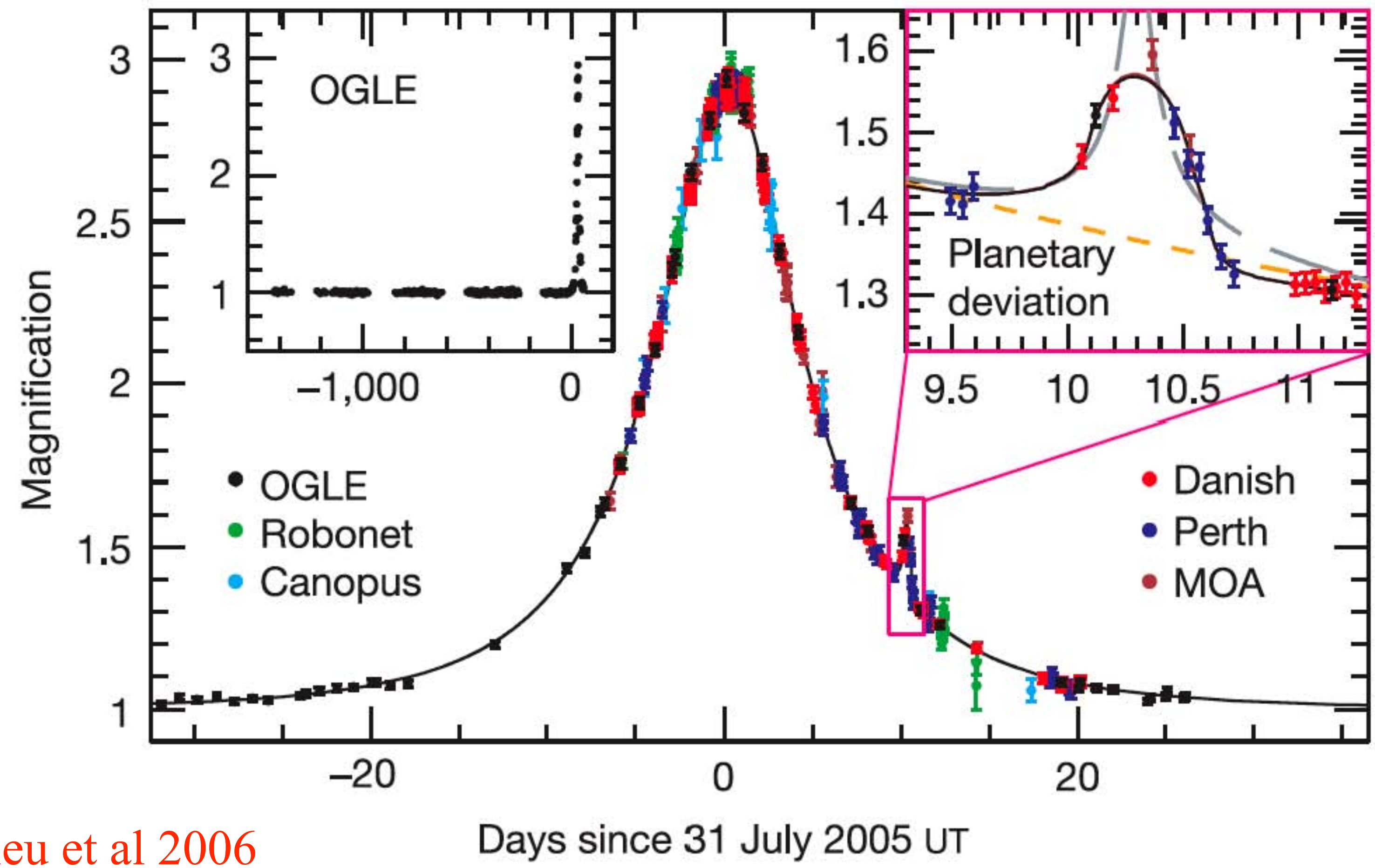
<u>Rotation would not be revealed without lensing magnification</u>

Jones et al MN 404, 1247 (2010)

Detecting Planets via Microlensing



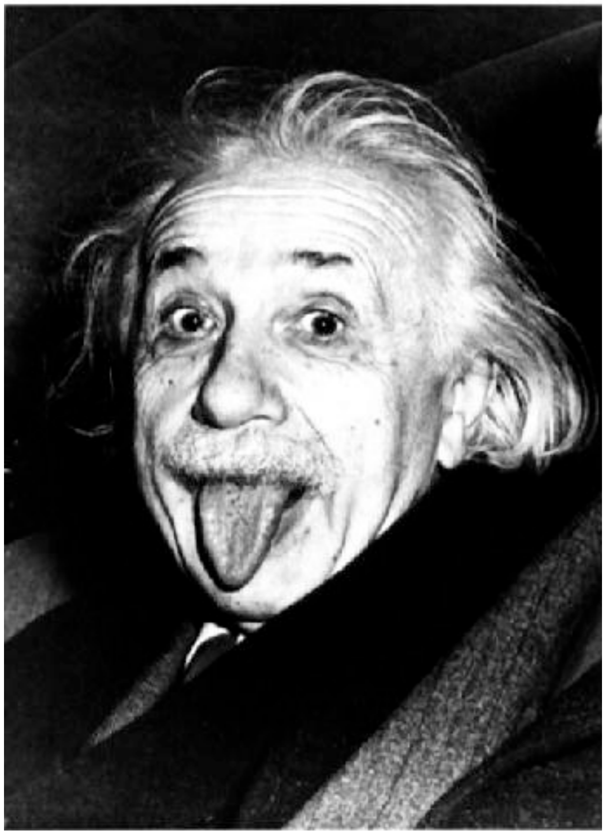
BLG390LB 5.5 Earth masses



Beaulieu et al 2006

Conclusions

Gravitational lensing has risen from obscurity, originally thought by Einstein to be of little practicality, into a significant tool for cosmologists (as Zwicky claimed)

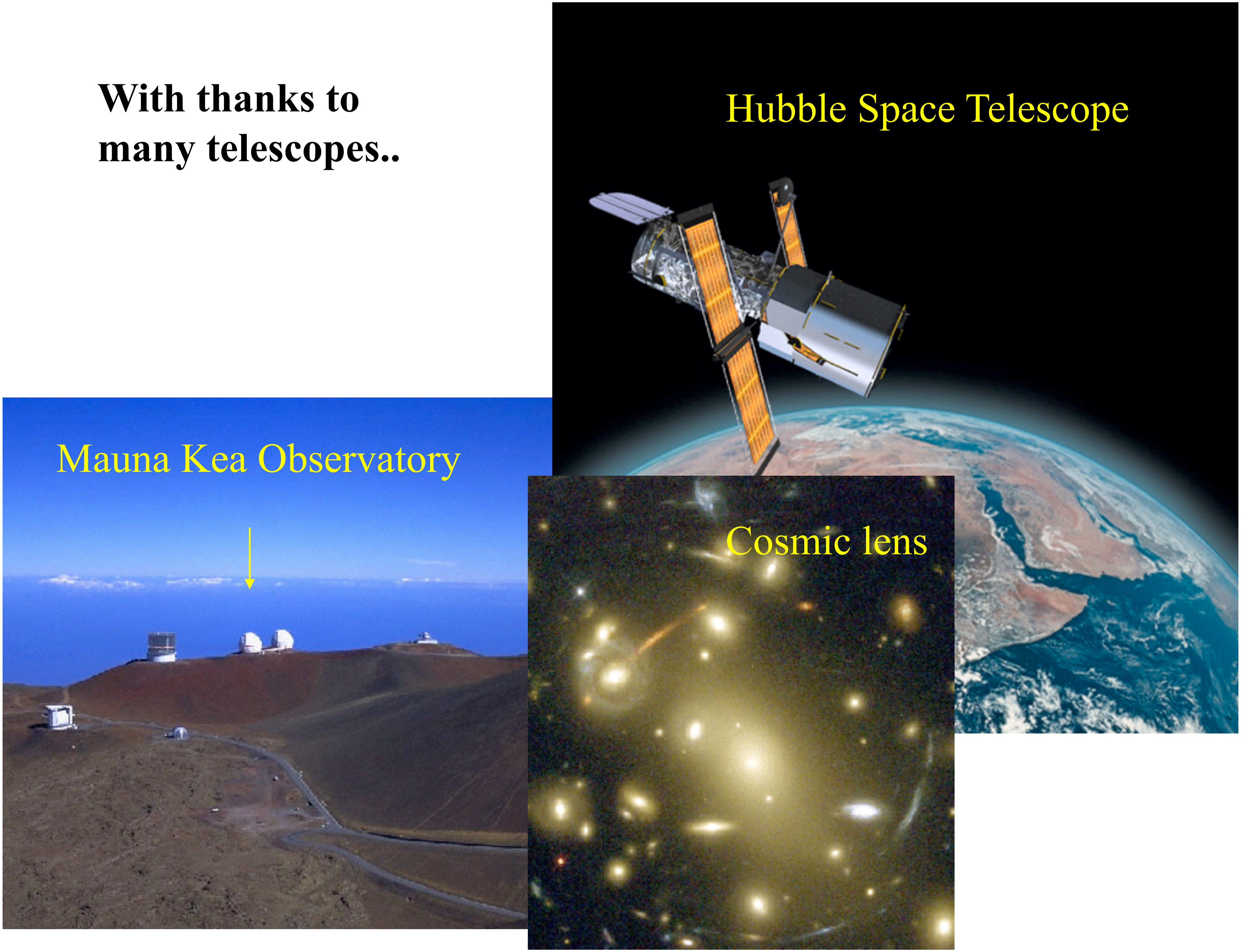


- The only precise probe of where the dark matter lies and how much there is, with promise of uncovering the nature of dark energy

- Enables us to magnify distant parts and secure our first glimpse of the earliest cosmic sources

- Can be used to search for abundance of Earth like planets in the Milky Way

With thanks to many telescopes..



[redacted]

Eclipses Before 1919 – a Sorry Tale

- Einstein finds assistant observer – Eirwin Findlay-Freundlich who tries for ten years to measure the deflection & never succeeds!
- Einstein writes to Hale inquiring whether deflection could be detected via Jupiter
- William Wallace Campbell (Director, Lick) races with Findlay-Freundlich to prove/disprove Einstein.
- US community remains very skeptical of GR through late 1920's

Aug 21 1914 Eclipse:- war breaks out week of eclipse!

- Campbell's equipment in Russia impounded
- Findlay-Freundlich arrested in Turkey

June 8 1918 Eclipse

- Campbell clouded out in Washington State

Was Eddington Biased in His Analysis?

- Eddington was clearly inspired by Einstein's theory
- He considered his verification of the deflection `the greatest moment' of his life
- Yet the deflection results from Sobral and Principe were at first sight discrepant and needed careful treatment
- Some consider he was so sure of the result that he discarded discrepant data so as to verify Einstein

e.g. John Waller (2002) Fabulous Science "a series of famous scientists whose passion and belief in a theory blinded them to contrary evidence" (including Millikan!)

Read Daniel Kennefick's excellent analysis on astro-ph/0709.0685
(see also Physics Today March 2009 p37)

Conclusion: Eddington was a man of principle and did not fudge his data!

Kennefick's Case in Support of Eddington

Principe : Eddington & Cottingham:

Astrograph: only 2 plates, 5 stars on each
Comparison plates taken at Oxford in February 1919
Analysis gave $\delta = 1.61 \pm 0.30$ arcsec

Sobral: Crommelin & Davidson

Astrograph: several plates, 12 stars on each but out of focus!
Comparison plates taken later in situ
Analysis gave $\delta = 0.93 \pm ?$ arcsec

4-inch lens: much smaller field but in focus
Comparison plates taken later in situ
Analysis gave $\delta = 1.90 \pm 0.11$ arcsec

Some argue Eddington discarded the Sobral astrograph to match GR prediction
Actually it was not Eddington but Dyson who discarded those data
Dyson did a further analysis of the Sobral astrograph assuming focus change did not affect the plate scale and got $\delta = 1.52$ arcsec

1979: Sobral plates were re-measured via machine: $\delta = 1.55 \pm 0.32$ arcsec