Galaxy evolution and cosmology with ELT interferometry

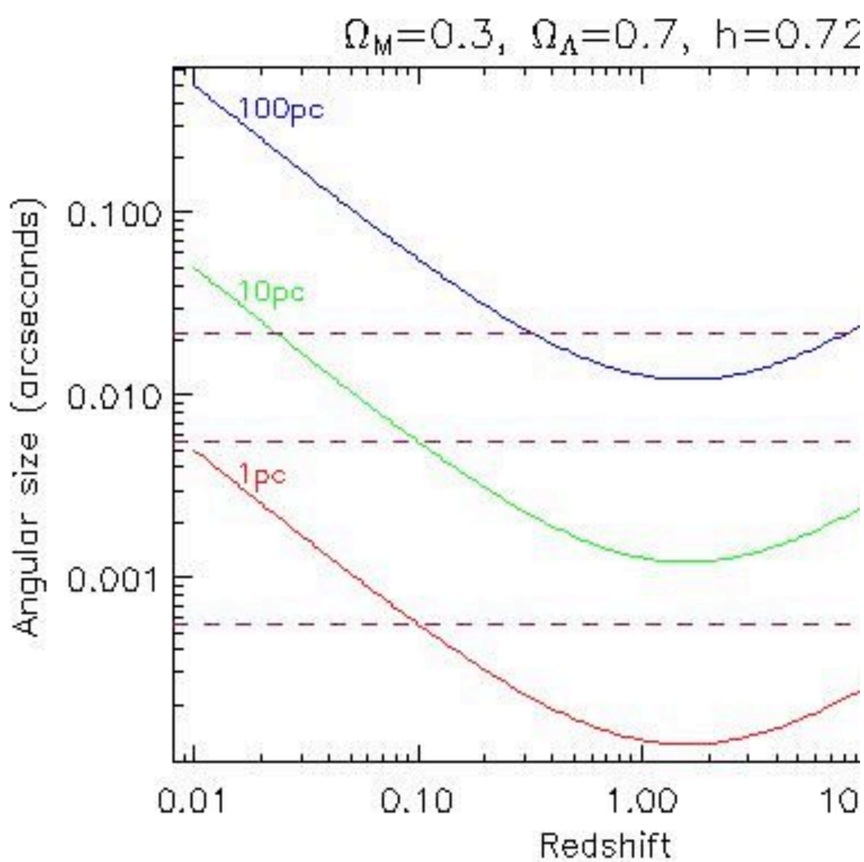
Stephen Serjeant, Future Directions for Interferometry, Tucson, USA, November 2006

Synopsis

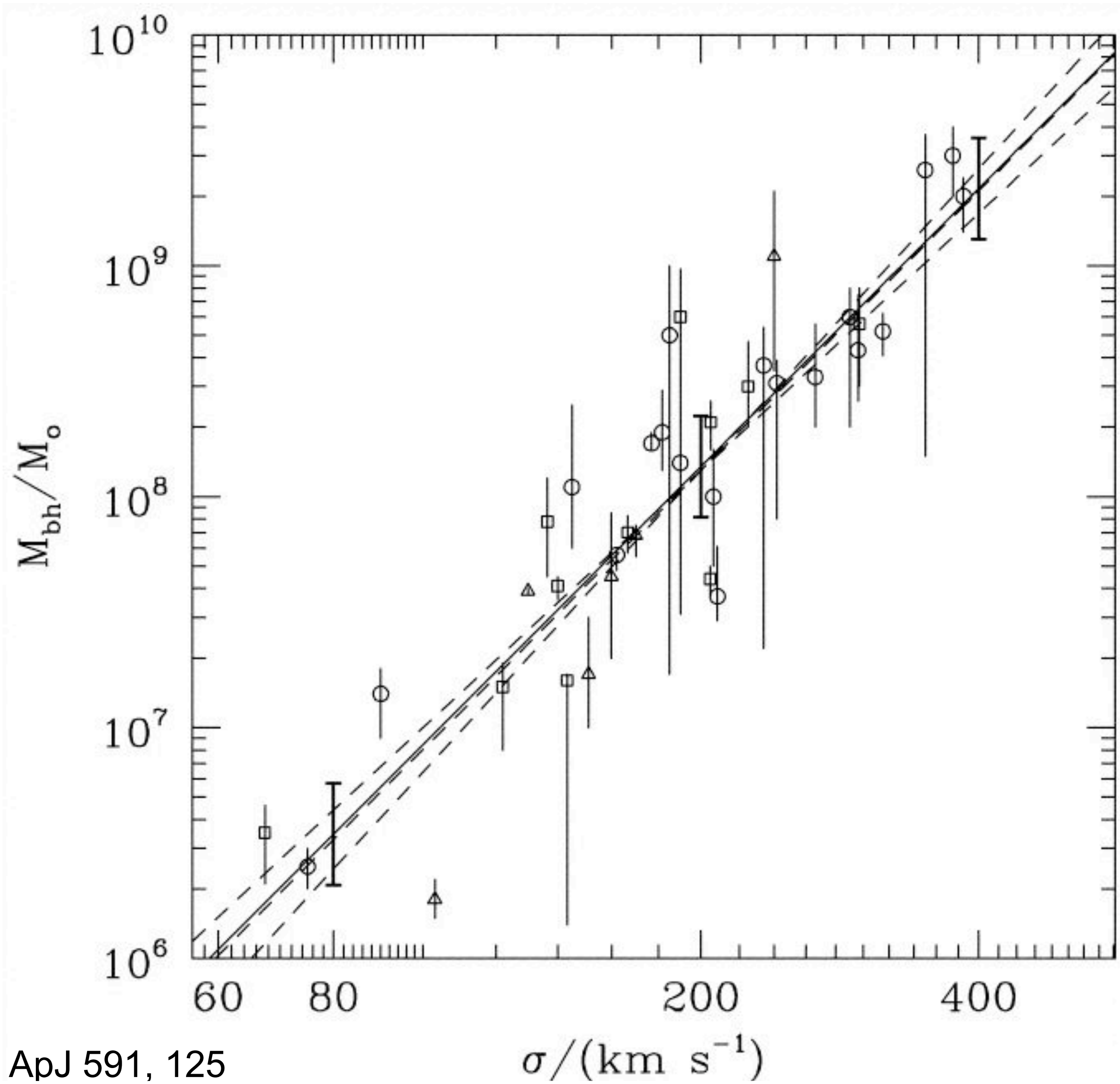
- Far Universe stuff
- Near-ish Universe stuff
- Possibly bonkers stuff
- Note: we allowed ourselves several luxuries
  - only consider the interesting physics on the relevant angular scales, i.e. no consideration of imaging interferometry practicalities
  - spectroscopy too...

Observing galaxies with an ELT interferometer

- Photon-starved cases: want big total collecting area
- Combining beams: is it easier to have a few big dishes than lots of small dishes?
- Small-scale resolution: want long baselines
- Large-scale resolution: structure larger than the primary beam of single dish is resolved out
- Gravitational lensing by a foreground cluster magnifies fluxes & some angular sizes by x10-100



Build-up of the Maggorian relation



Adams et al. 2003 ApJ 591, 125

Build-up of the Maggorian relation

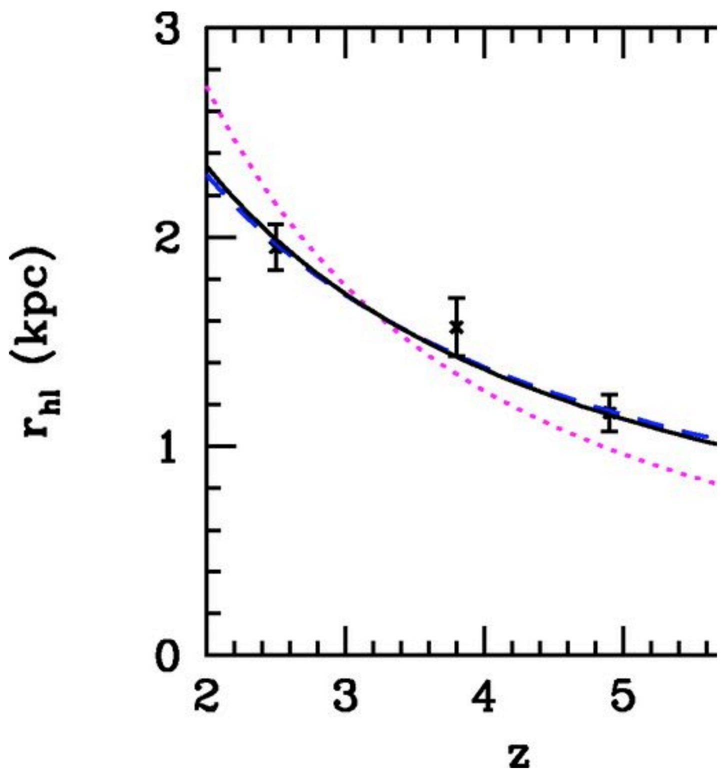
- Broad line region ~1pc ⇒ too small except in nearby Seyferts
- Stellar dynamics in SMBH gravitational sphere of influence is accessible:

$$r_i = \frac{GM_{\mathrm{BH}}}{\sigma^2} = 4.3\,\mathrm{pc}\left(\frac{M_{\mathrm{BH}}}{10^7 M_{sun}}\right)\left(\frac{\sigma}{100\,\mathrm{km\,s^{-1}}}\right)^{-2}$$

- Direct BH mass measurements for any AGN with $M > 10^6 M_\odot$ at $z<0.1$ or $M>10^9 M_\odot$ at any redshift
- Direct tests of theoretical descriptions of spheroid stellar mass assembly regulated by AGN feedback
- Limited by spatial resolution
- Does BH growth via direct accretion dominate over mergers?

z~6 galaxies

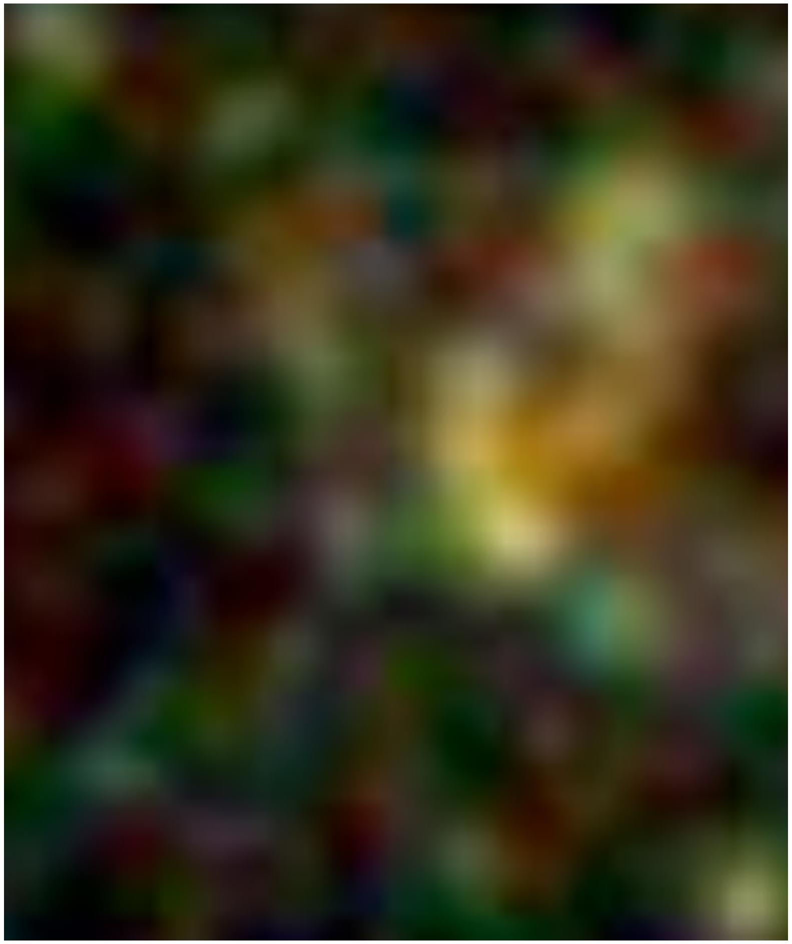
- These galaxies have the smallest angular sizes of any known galaxy population
- The half light radius of 0.3-1.0L* galaxies is about 1kpc (170mas) at z=6
- Kinematics better done with single ELT (flux bigger than primary beam resolved out) but substructure accessible to interferometer



Bowens et al. 2004 ApJL 6

The Ly α and Ly continuum escape fractions

- Determined by morphology of ISM
- Milky Way Ly continuum f_{esc}≈1-2%. Local starbursts f_{esc}<6%
- High redshift: disputed claims of f_{esc}≈50-100% at z ≈3.5
- Submm-selected galaxies: optical morphologies heavily affected by inhomogeneous dust, but Lyα detections suggest SNe-driven winds driving channels of lower obscuration



3''x3'' BVI image of z=2.743 submm galaxy. et al. 2004 ApJ 616, 71

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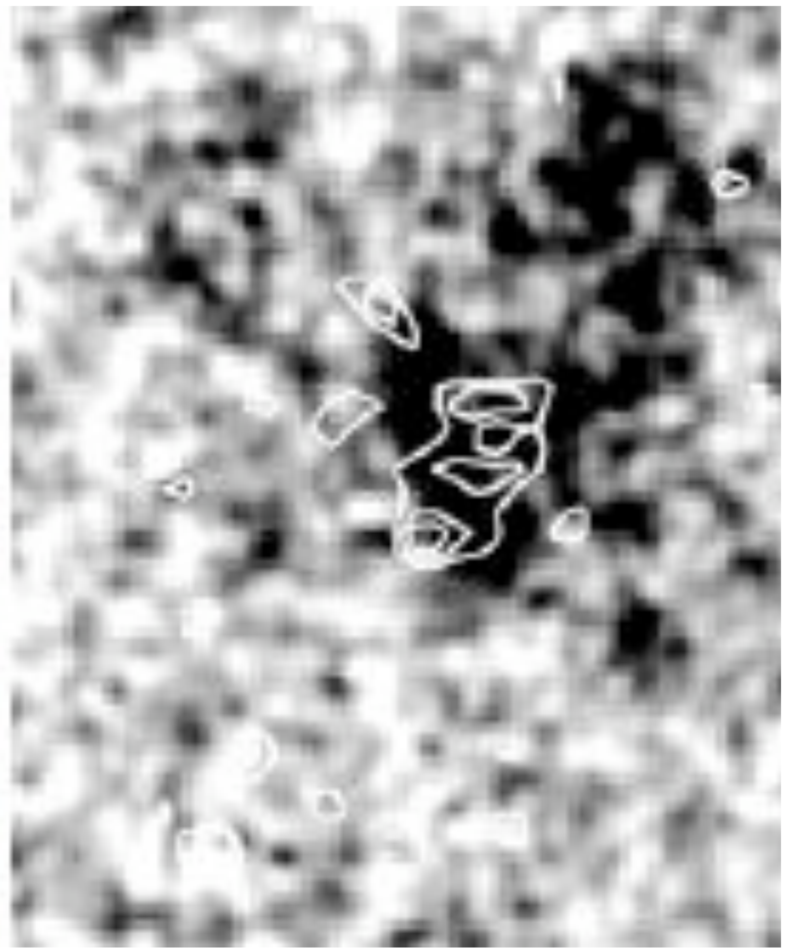
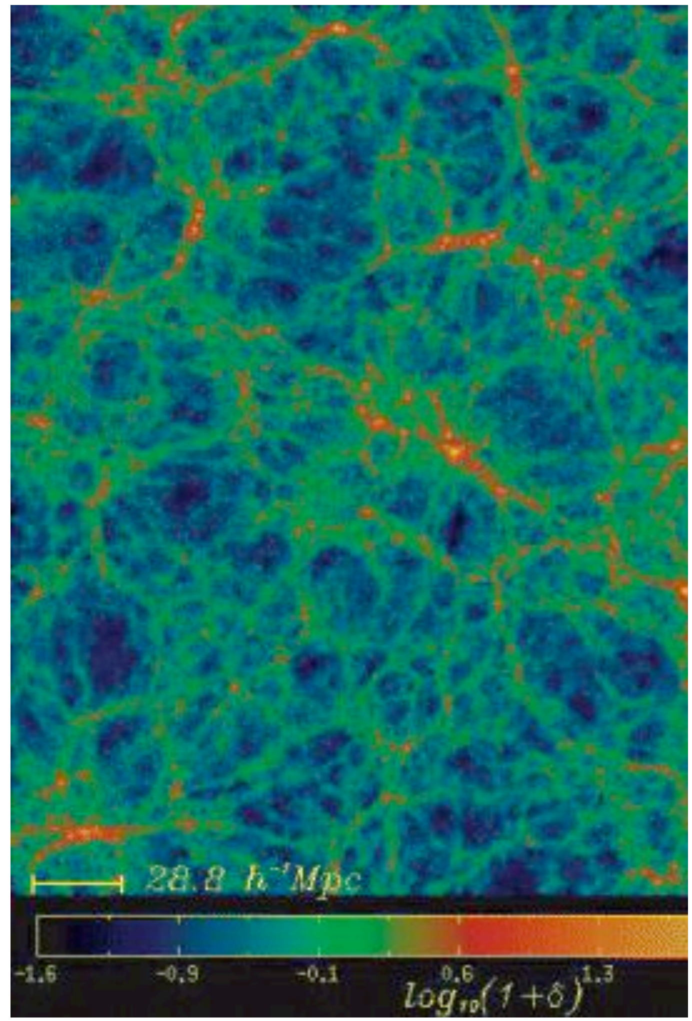


3’’x3’’ V-band image and 1.4GHz contours of submm galaxy. Chapman et al. 2004 ApJ 61

What do higher-z galaxies look like?

- Structure at small scales (e.g. 10pc) present at any accessible redshift up to and including zero
- Comoving clustering pattern of first stars and galaxies may be similar to present-day dwarf galaxies
- First light perhaps $z \approx 25$; reionization $z \approx 11$ (WMAP). This extraordinary change took only ~250 Myr



Gao et al. 2005 MNRAS 36

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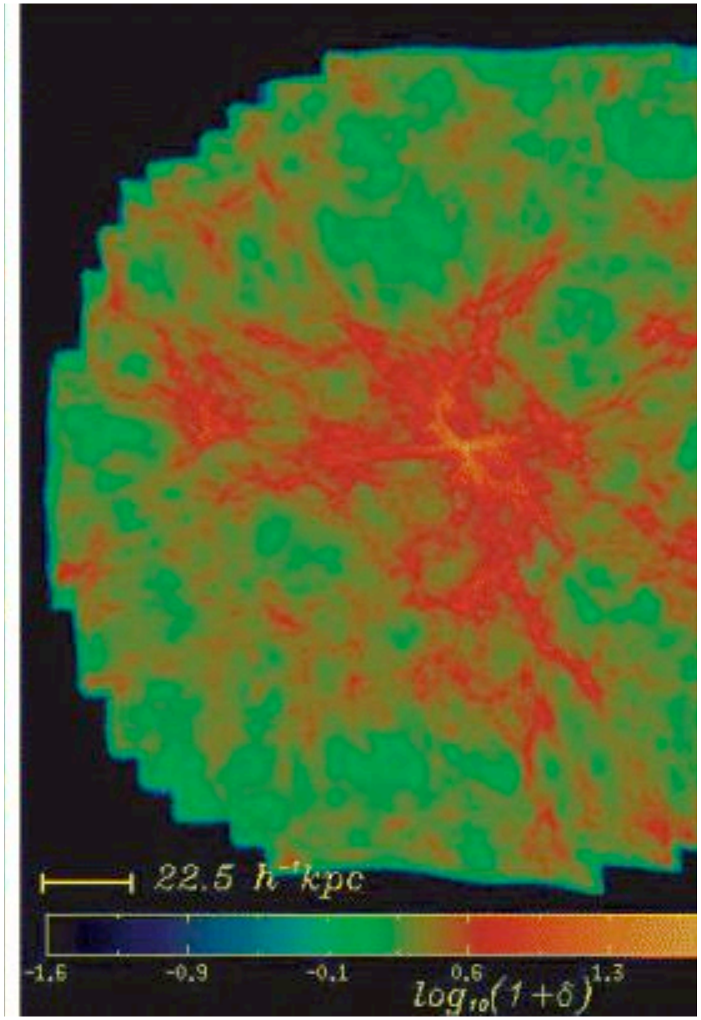


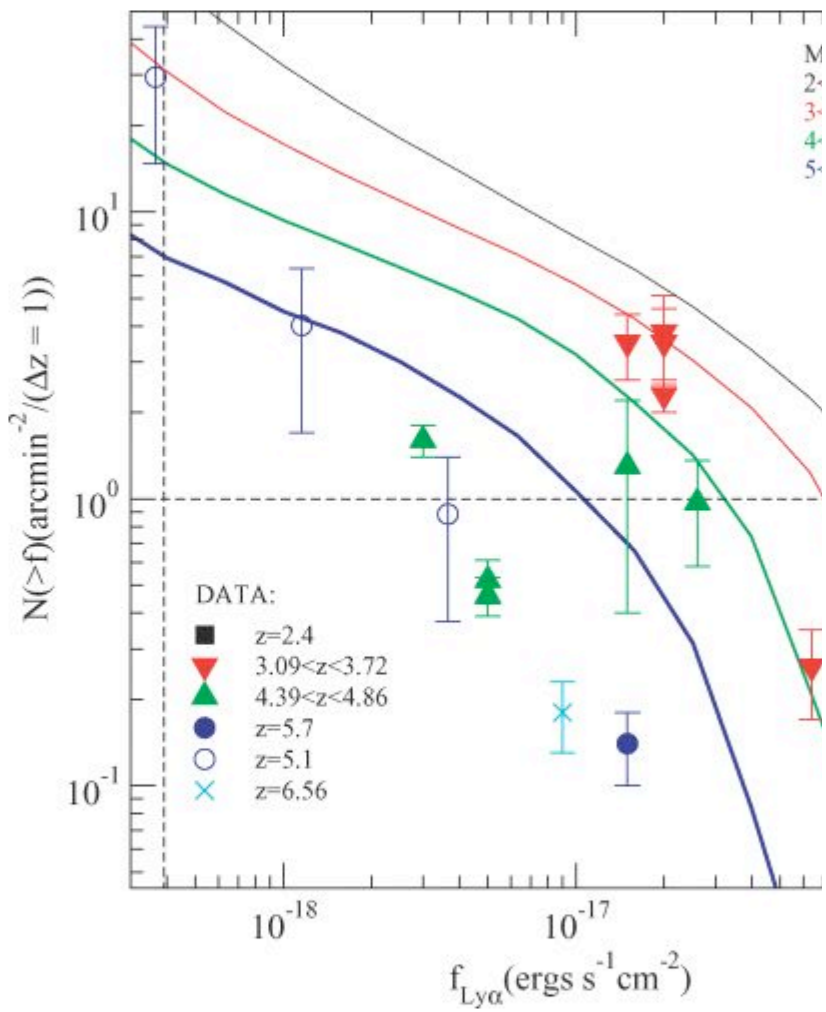
Gao et al. 2005 MNRAS 36

What do higher-z galaxies look like?

- But how to go from dark matter to baryons?
- $\rho \propto (1+z)^3 \Rightarrow$ may well be qualitatively different to loca Universe
- Should see knots of star formation, perhaps the sites c globular cluster formation
- Should also see large-scale shocks from "galaxy"-wide starburst-driven winds. Local Universe analogies suggest collimated bipolar flows?

What do higher-z galaxies look like?

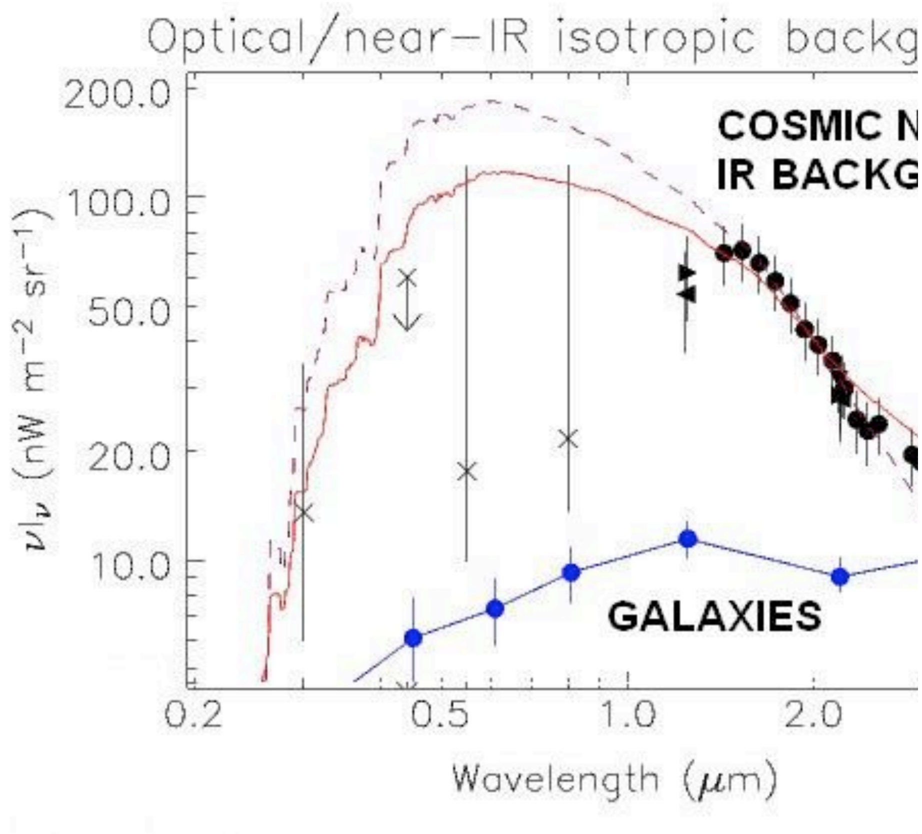
- Very few objects with $10^{10} M_\odot$ collapse before z=8
- Bland-Hawthorn & Nulsen (astro-ph/0404241): 10^8-$10^{10} M_\odot$ collapse at $z \approx 8$ with Lyα fluxes of $\approx 3 \times 10^{-18}$ ergs s^{-1} cm^{-2}
  - around 90-99% spread over <5kpc (<1'') from external large-scale shocks
  - around 1-10% from scattered light from compact star forming region ($\approx$ 100pc or 0.02''). NB scattering medium likely to be clumpy
- $\approx$10 sources arcmin^{-2} with Lyα in the J-band with fluxes of $\approx 3 \times 10^{-19}$ ergs s^{-1} cm^{-2} objects predicted



Le Delliou et al. 2005 MNRAS 3

What do higher-z galaxies look like?

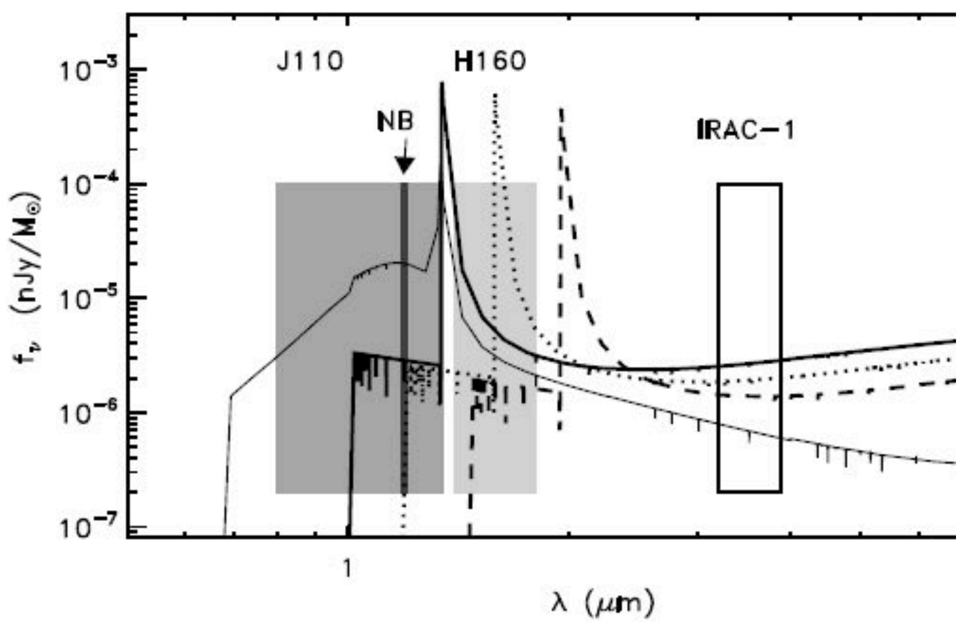
- High values of cosmic near-IR background from DIRBE and IRTS not confirmed by γ-ray absorption of blazars
- DIRBE/IRTS detections may be dominated by scattered solar light; spectrum almost identical
- Nevertheless, there is excess γ -ray absorption compared to resolved near-IR populations, e.g. a few nW m^{-2} sr^{-1}



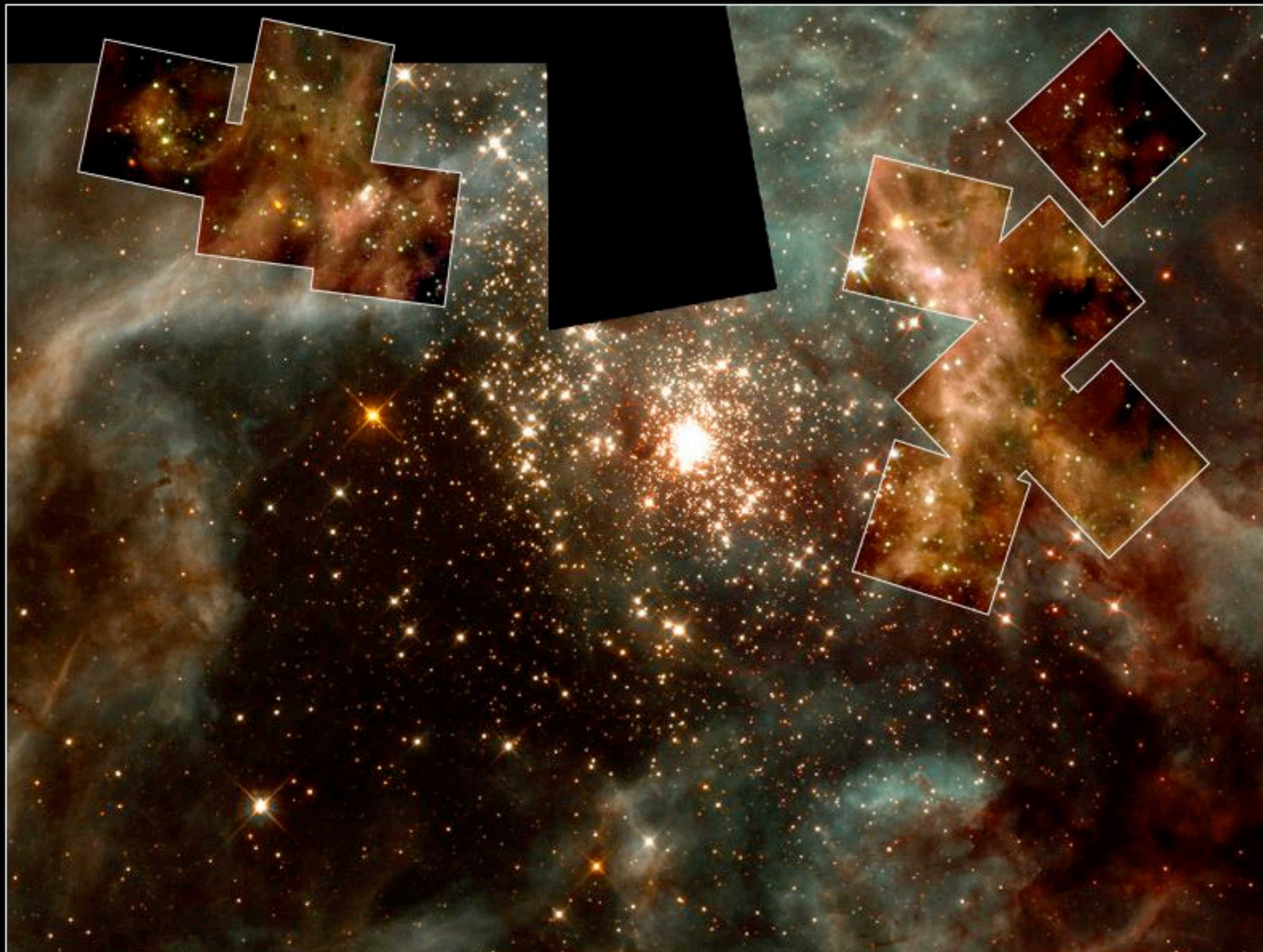
Adapted from Serjeant 2006 in prepai

What do higher-z galaxies look like?

- Cosmic near-IR background fluctuations suggest 3.6μm fluxes <10nJy, probably from the z>10 reionization population. Suggests K>27, H>27.5, J>28 (for f_ν=const) i.e. AB mag > 29
- Fluxes suggest objects have ~10^5 stars; c.f. *z*=0 super star clusters with half light radii ~10pc?
- Low metallicity ⇒ strong NIV, CIV, HeII etc ⇒ have ionization and metallicity constraints
- 1-2μm ELT interferometry follow-up to JWST detections?



Kashlinsky astro-ph/0610943. SEDs of population III object at z=10,12,15.



30 Doradus Nebula in the LMC **HST** • WFPC2 • NICMOS

PRC99-33a • STScI OPO • N. Walborn (STScI), R. Barbá (La Plata Observatory) and NASA

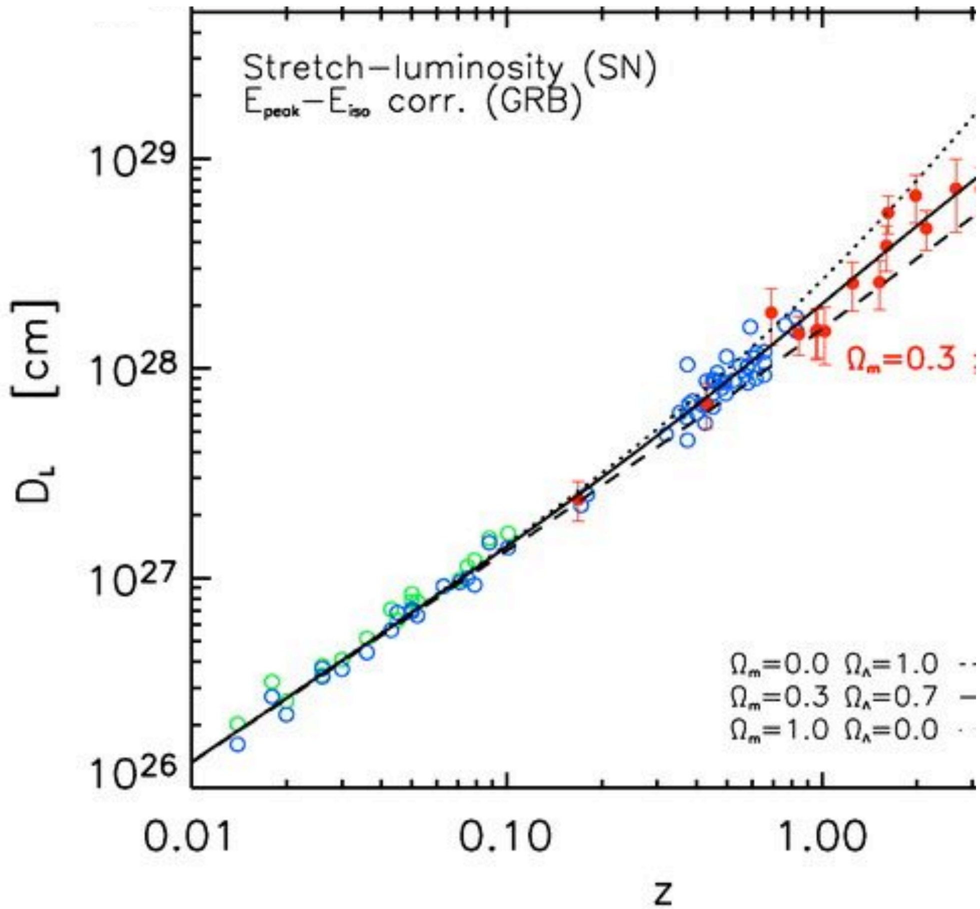
NICMOS box size $\equiv$ 4.8pc

High redshift supernovae

- Spectroscopic redshifts possible in 4 hours for type 1a SNe to z=1.7 with a single-dish 30m ELT
- Few pc-scale environments of SNe: geometric distanc
- Possible to probe evolution in dark energy equation of state
- However, discovery requires wide-field ELT imaging survey: ≈1-2 SNe of all types per year per square arcminute.

Another possible high-z standard candle

- Possibility that gamma-ray bursts may be useable as standard candles via the correlation between collimation corrected energy and spectral peak energy (c.f. stretch-luminosity correction in SNe 1a)
- Again, environment of GRB with imaging interferometer



Ghirlanda et al. 2004 ApJ 613, L13

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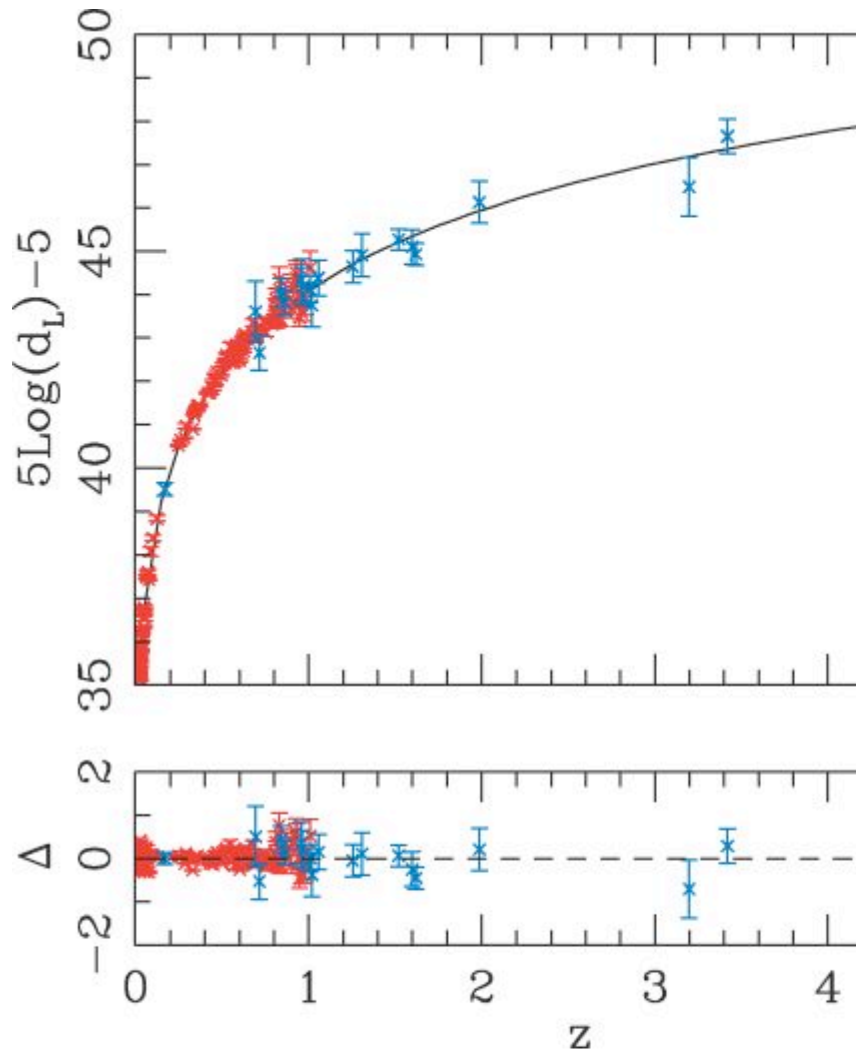

Firmani et al. 2006 MNRAS 372, L

High redshift gamma-ray bursts and quasars

- Probe of reionization epoch
- Probe of intervening intergalactic medium
- Studies of GRB host galaxies after the transient has faded
- GRBs do not require a SMBH so may exist at higher *z* than quasars
- Metal absorption lines during GRB yield systemic redshifts more accurately than in Lyman-break galaxies or those selected by Lyα emission

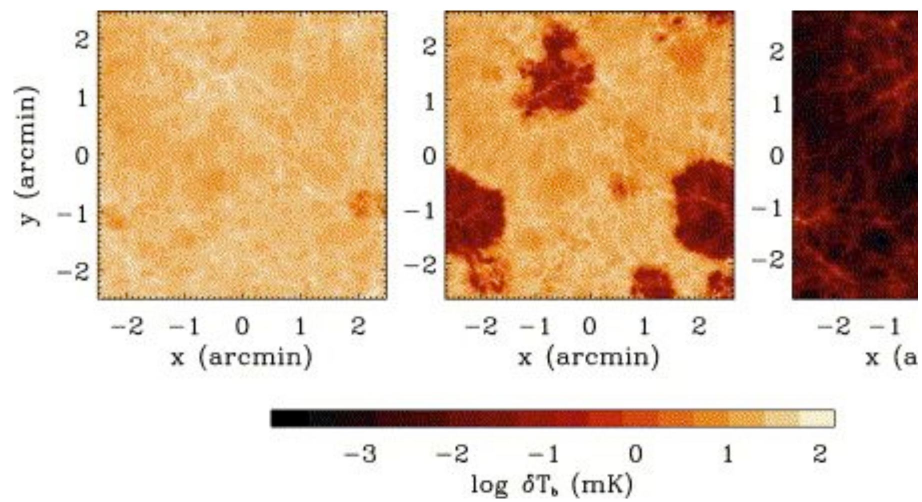

Figure shows 21cm brightness temperature at z=12.1, 9.2, and Taken from Furnaletto et al. 200 MNRAS 347, 187.

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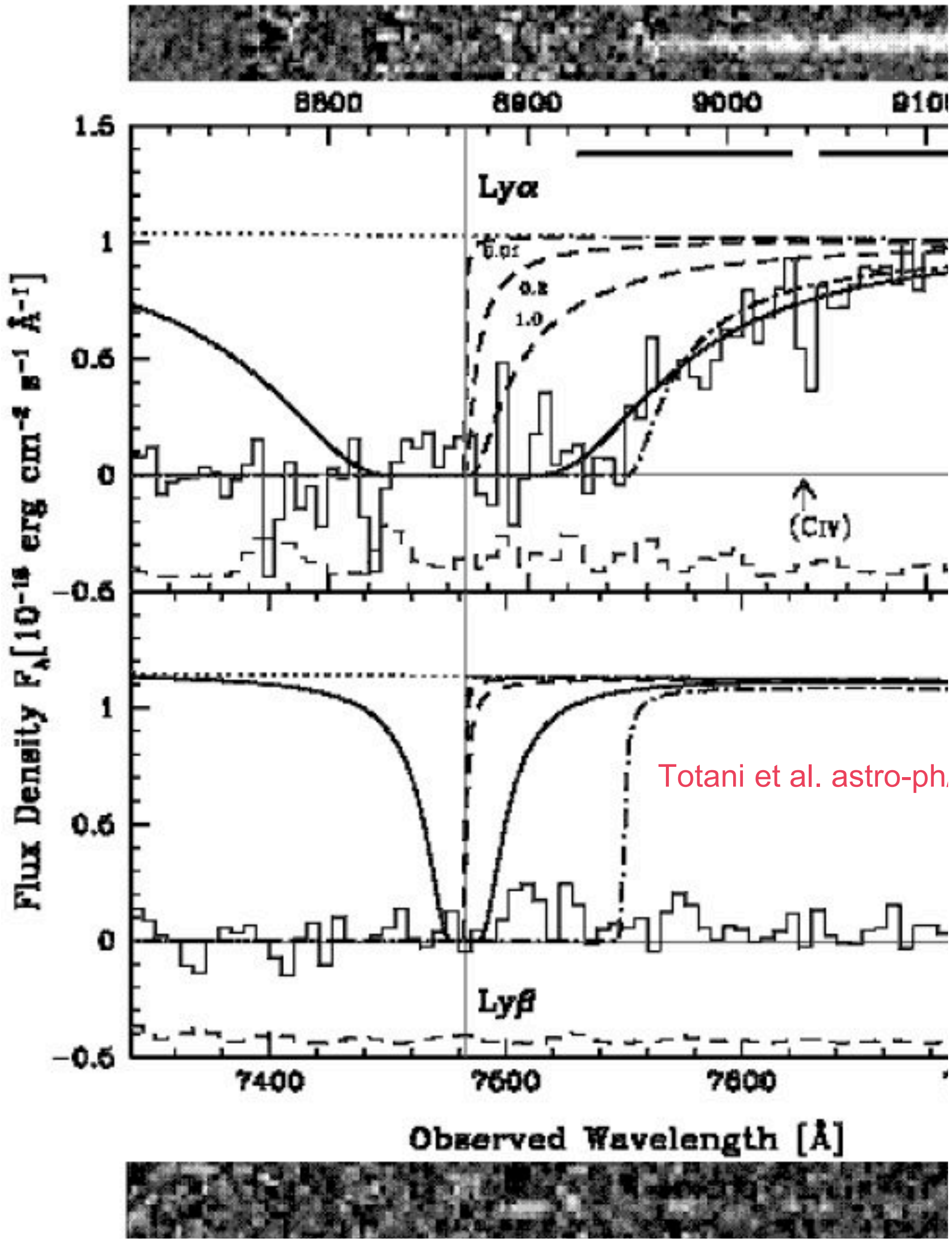


Stellar populations in external galaxies: imaging

- Local group not at all representative
- Low-mass stars have lifetimes ~$1/H_0$
- Neglecting interferometer losses, ELT interferometery with ≥10(baselines could detect pre-MSTO stars to Virgo by beating dow confusion noise. N.B. $1M_{\odot}$ star at Virgo has V≈35.5
- Colour-magnitude diagrams of resolved stellar populations, covering an overdensity range of x100, and covering the entire Hubble sequence
- Tests key predictions of cosmological models: e.g.:
  - Are there old disk stars at large galactocentric distances?
  - Are the ages of inner disk stars similar to bulge? Distinguishe bulge formation scenarios

Stellar populations in external galaxies: spectroscopy

- More powerful probe of chemical evolution of a galaxy: outer regions of RGB stars mainly unprocessed gas ⇒ fossil record of ISM metal enrichment at time of star's formation
- CaII triplet detectable in old RGB stars in Virgo (V=28)
- Higher resolution spectra (R>20,000) necessary for abundance ratios etc

Object	$(m-M)_0$
LMC	18.5
M31	24.3
Sculptor Group	26.5
M81/82	27.8
Cen A	28.5
NGC 3115	30.2
Virgo Cluster	30.9
Antennae Galaxy	31.5
50 Mpc	33.5
Arp 220	34.5
Perseus Cluster	34.5
Stephan's Quintet	35.0
Coma Cluster	35.0
Redshift $z \approx 0.1$	38.5
Redshift $z \approx 0.3$	41

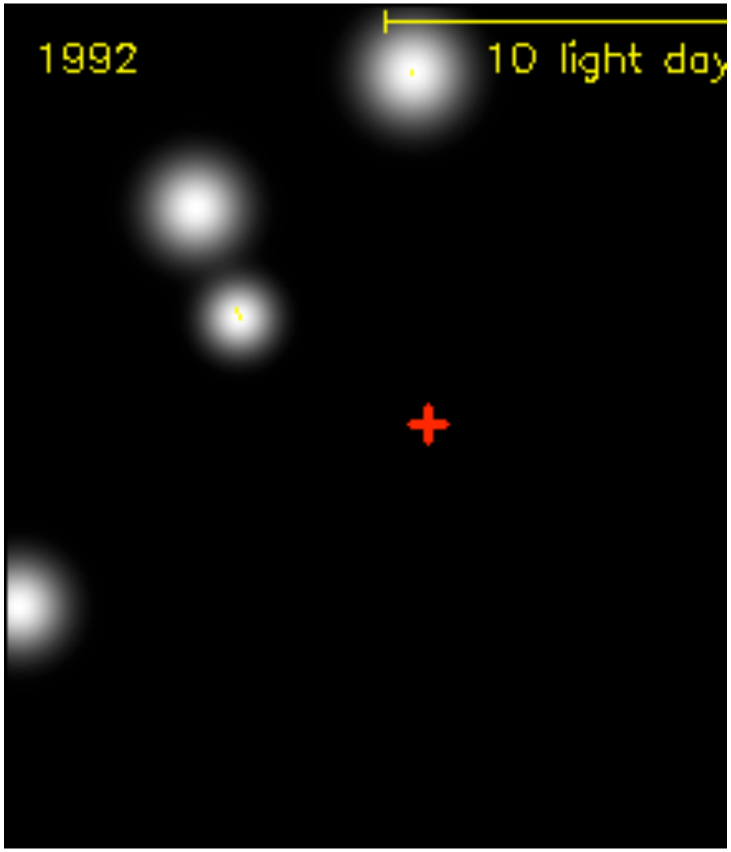
Table plagiarized from European ELT science c

Distance indicators from stellar populations

- Tip of red giant branch: $M_V \approx -2$, $M_I \approx -4$, $M_K \approx -6$. Limited by confusion in crowded fields $\Rightarrow$ interferometr suggesting 100m baseline could reach to Coma cluste
- RR Lyrae stars would be observable to Virgo, similarly
- Cephids have $M_V \approx$-2.5 to -7.5
- Surface brightness fluctuations?
- Calibrates secondary distance indicators

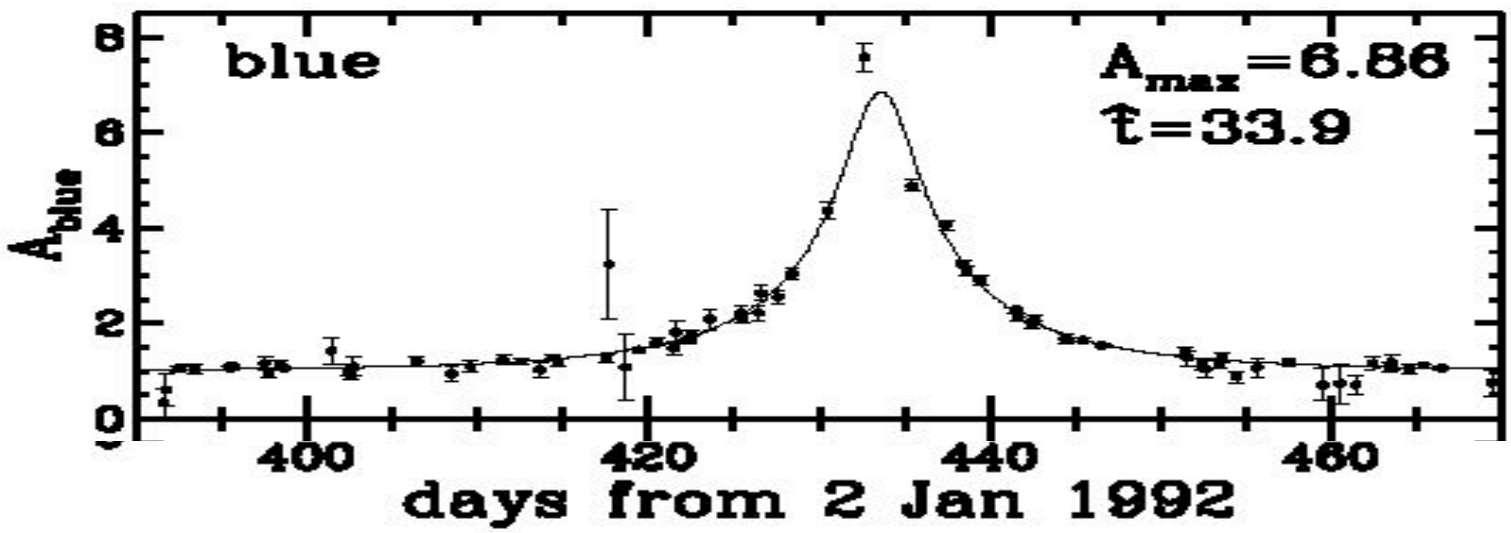
The SMBH in the Galaxy

- Resolutions of a few mas can probe distances of a few light hours from the central SMBH, testing relativistic orbits within 10-100 Schwarzschild radii (NB stellar centroids much better determined than θ_{PSF})



~0.5'' box side. From www.mpe.mpg

Gravitational microlensing



Gravitational microlensing

- $\theta_E \approx 0.1$mas – requires a >1km baseline
- Obtaining θ_E and magnification separately determines distance.
- Resolving lens from star (e.g. after microlensing event) is easier
  - 0.05 $M_{\odot}$ brown dwarf at 1kpc has J=28 and K=29; requires R≈100 near-IR spectra to get methane and perhaps ammonia
  - 0.5 $M_{\odot}$ DA white dwarf 15 Gyr old at 50kpc has V≈3

Gravitational macrolensing

- Lensing by supermassive black hole in Galactic centre:
  - deficit of stars within 10 mas of centre
  - surplus of stars within 30-300 mas of centre
- Stellar mass surface density in central ~10'' is $\approx 10^5 M_\odot$ arcsec^{-2}

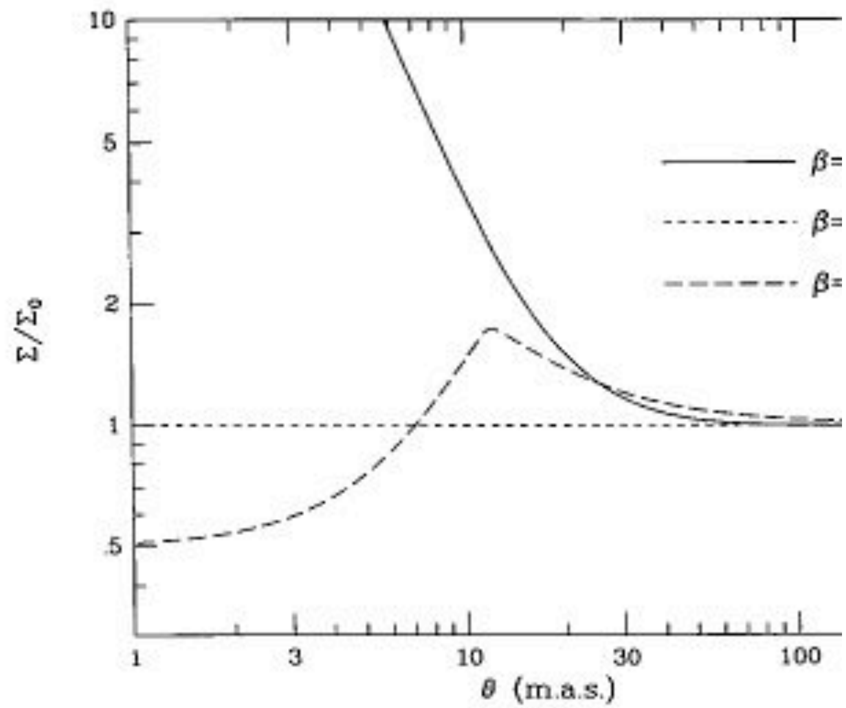
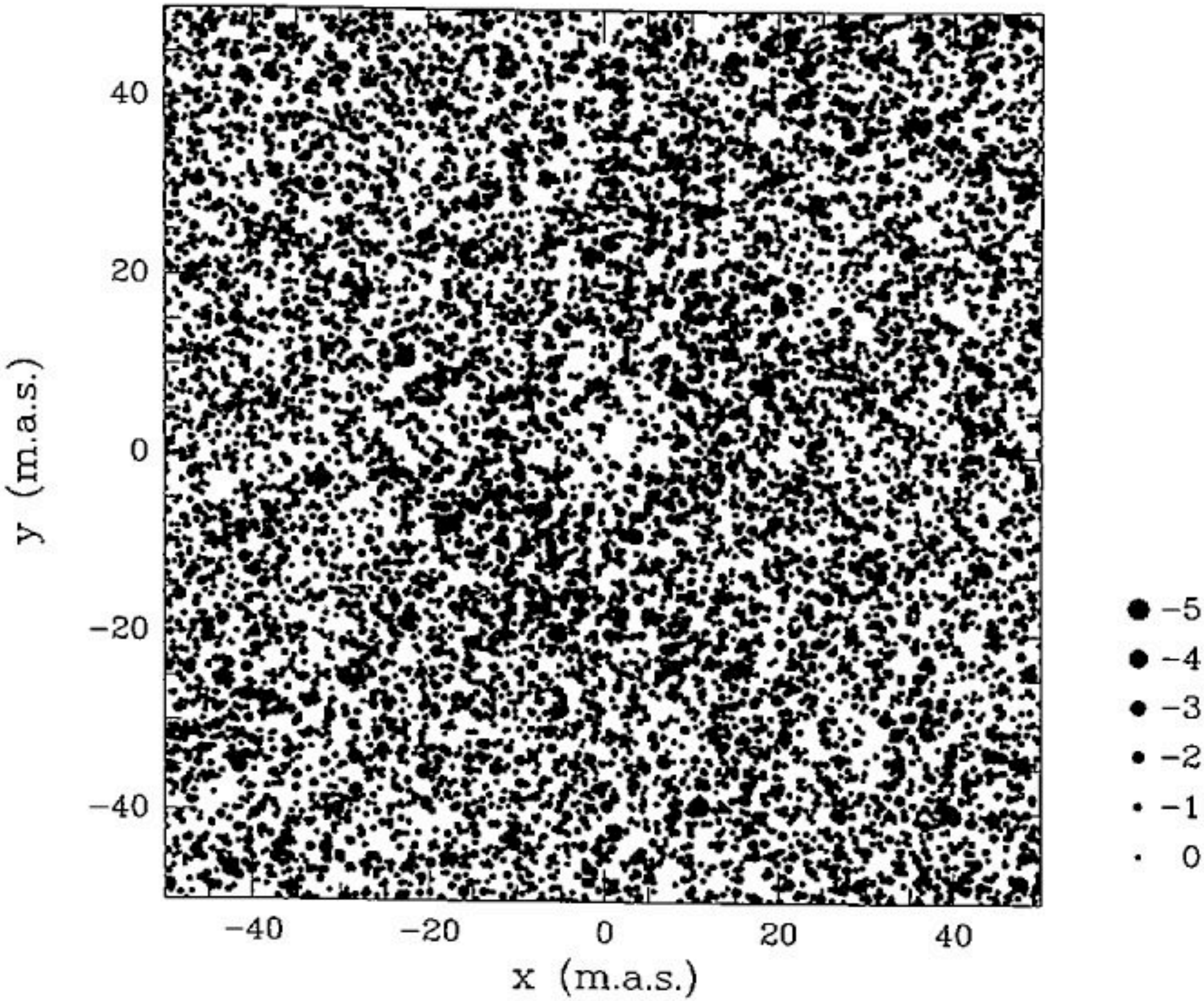


FIG. 1.—Apparent surface density of stars in the plane of the
function of angular distance from Sgr A*, relative to the surface den
absence of gravitational lensing. The parameter β is the slope of
luminosity function: the fraction of stars with apparent luminosi
than f is assumed to scale as $f^{-\beta}$, with the luminosity function extend
to a flux f_1, 1% of the flux limit f_{min} (see text).

(Wardle & Yusef-Zadeh 1992 ApJ 387



Wardle & Yusef-Zadeh 1992 ApJ 387, L65. 10^6 stars arcsec^{-2} in absence of lensing, β=2, μ_{max}:

Gravitational macrolensing

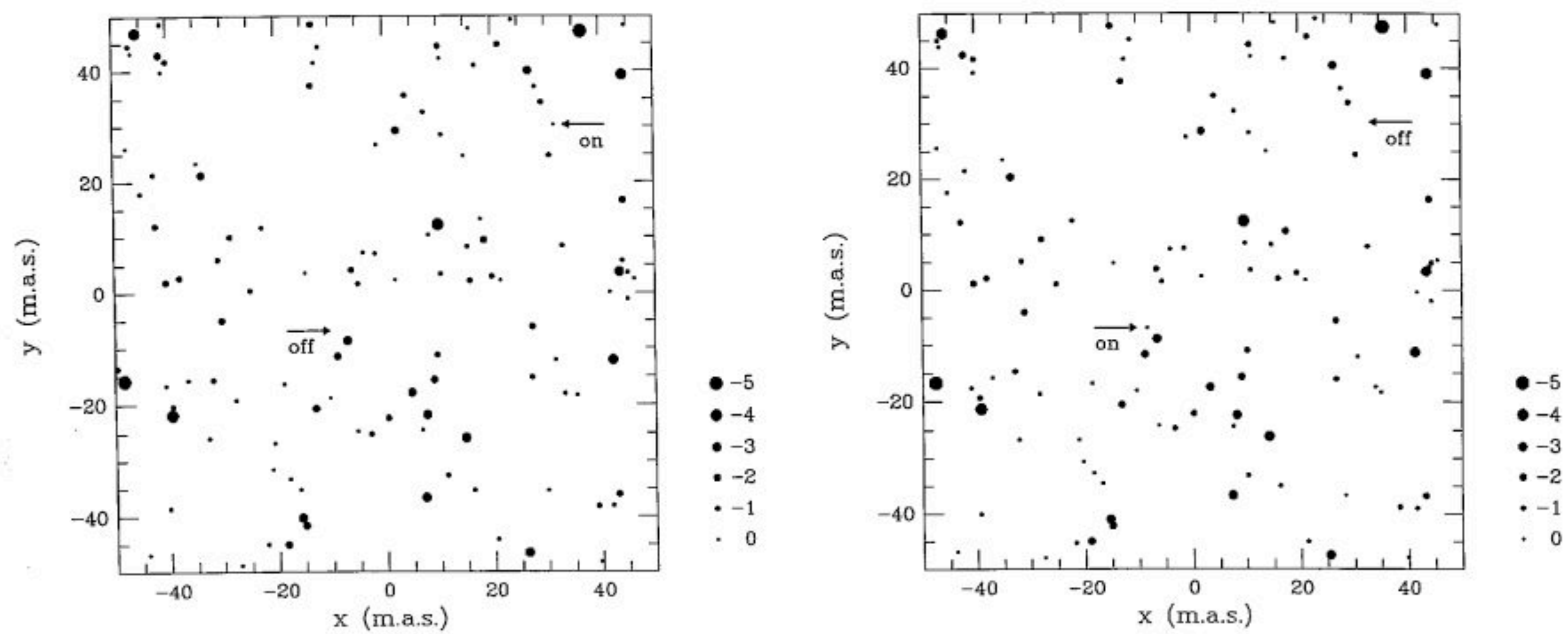


FIG. 3.—Simulation of the appearance of the field at epochs separated by 1 yr for $f_{min} = 100 f_1$, $\beta = 1$ and $\Sigma_0 = 10^6$ arcsec^{-2}. Amplification of faint stars above the detection threshold results in transient sources which are visible for months or years. Those that appear or disappear between the two epochs are arrowed.

Wardle & Yusef-Zadeh 1992 ApJ 387, L65. 10^4 stars arcsec^{-2} in absence of lensing, β=1, μ_{max}:

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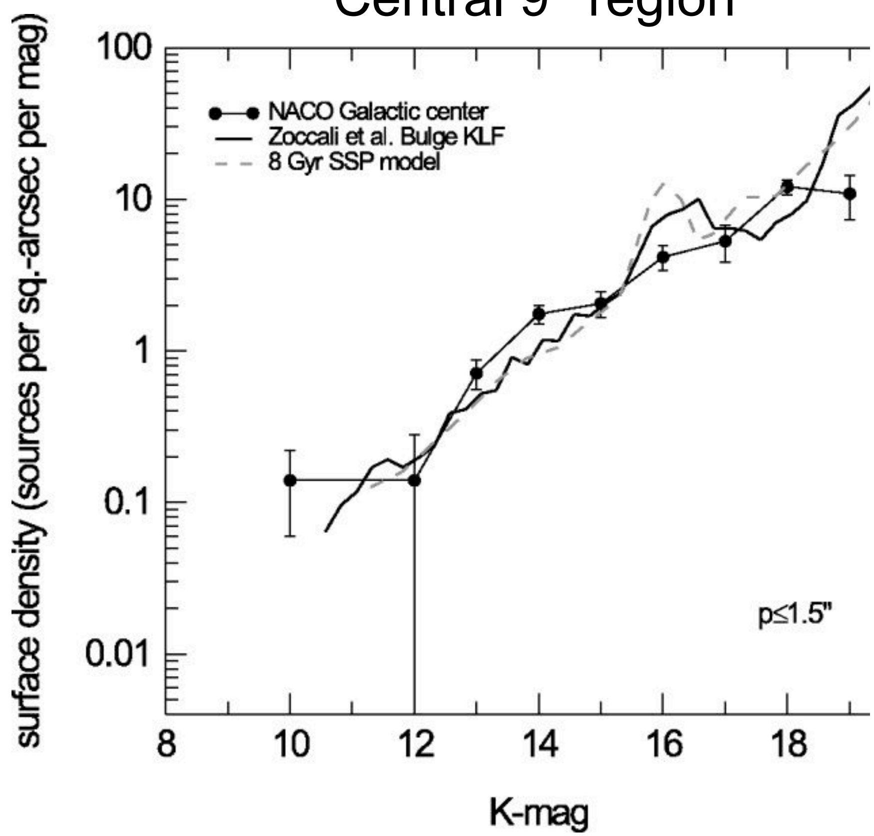
Central 9'' region



(Genzel et al. ApJ 594, 812)

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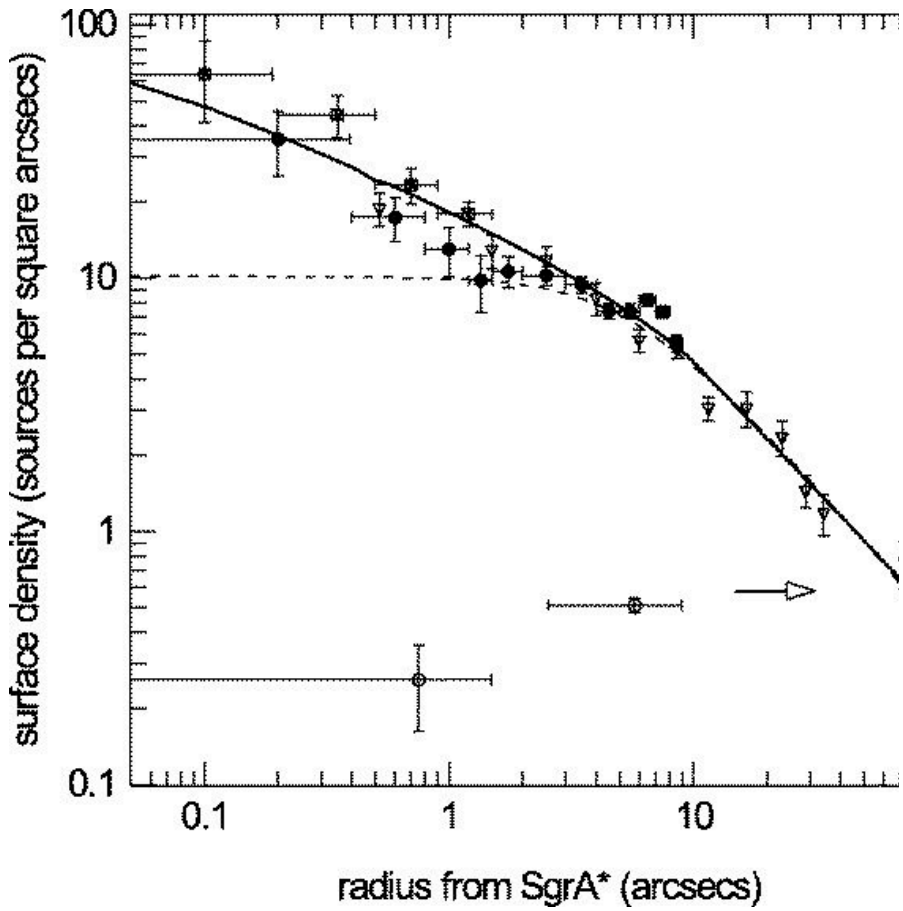

Surface density of K ≤17 stars near

A test of quantum gravity?

- Several authors have (controversially) suggested spacetime graininess may be detectable via halo structures in interferometric fringes
- Effects inversely proportional to wavelength ⇒ VLBI no use
- Haloes (if they exist) would have radii ≈ 0.2mas at 1.6μm

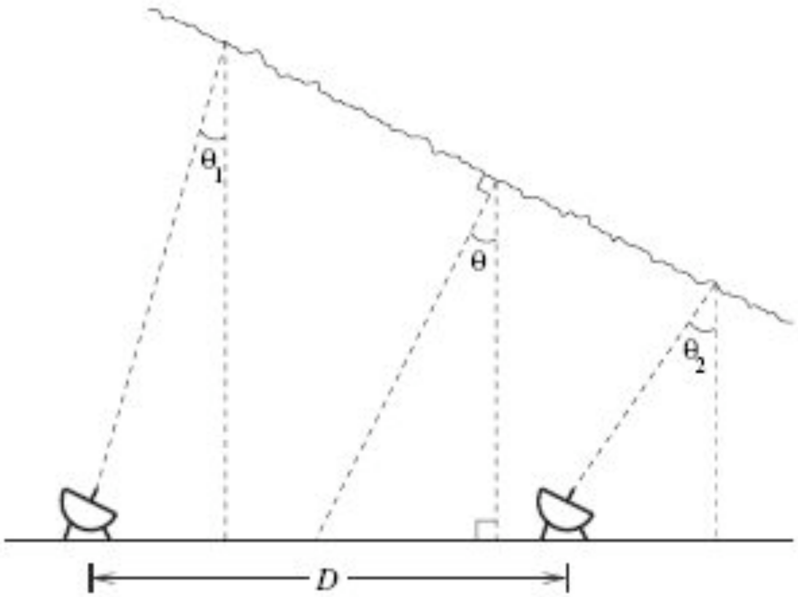

FIG. 1. Interferometer observing an incoming electror wave from a distant galaxy. The tiny corrugations exaggerated in the figure) in the wave front are due to sp foam-induced fluctuations in phase velocity.

Christiansen et al. 2006 Phys. Rev. Lett. 96, (
but see also Chen & Wen gr-qc/0605093

Summary

Are there well-posed fundamental cosmological questions that onl
an ELT interferometer with 100-1000m baselines will answer?
Answer: probably not! *But the following might be interesting if they are possible:*

What reionized the Universe, and how? (e.g. JWST follow-ups)

- Lyα from the reionization population
- Population III supernovae
- Filling factor of first Stromgren spheres during reionization and metallicity of early Universe IGM: absorption against ultra-high-z point sources

Why the Maggorian relation?

The microphysics of gas accretion and feedback (resolution is essential): e.g. resolving HII regions and winds at high-z

Chemical abundances and star formation histories in the local Universe

What is w? RGB tip, SB fluctuations, distant SNe, γ-ray bursts

Gravitational micro/macro-lensing (including direct MACHO lens detections)? Strong field gravity? More exotic & speculative physic


"That's all Folks!"