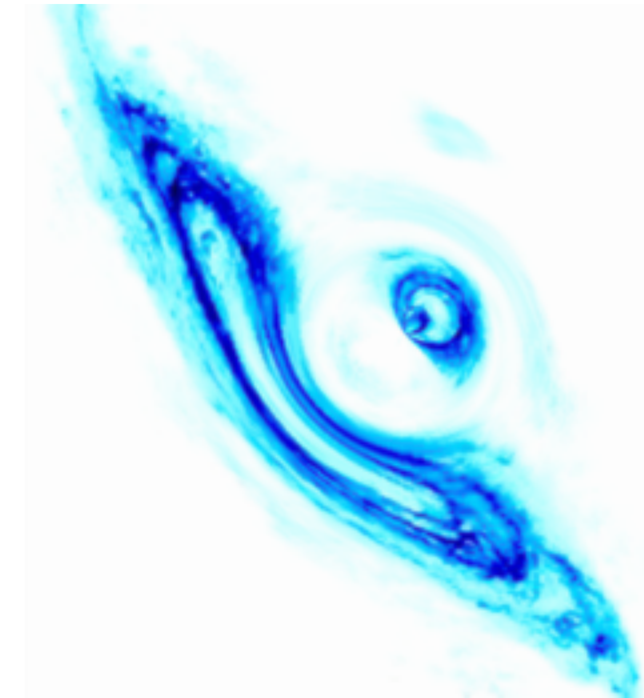
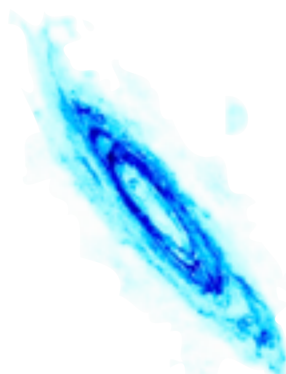
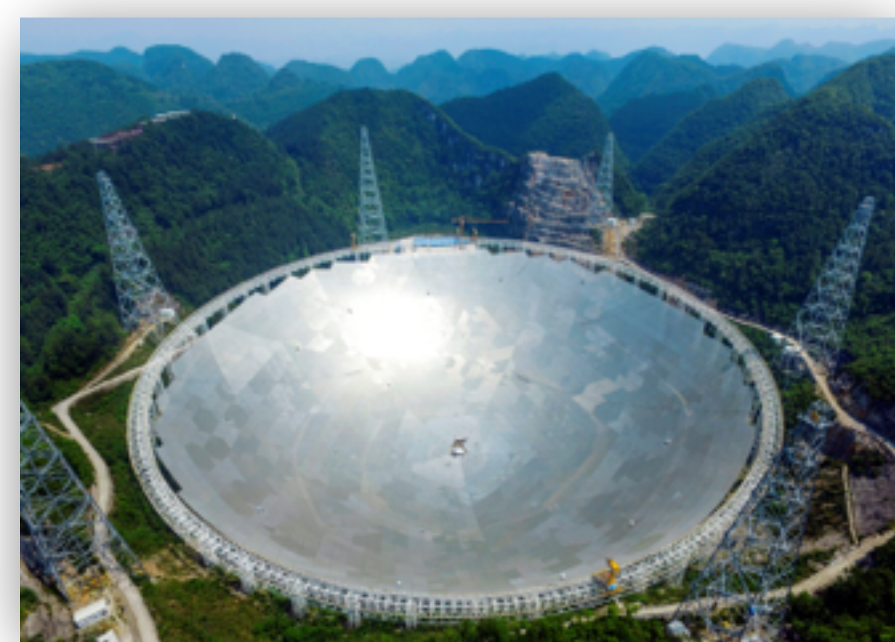


Gravitationally lensed HI

synergies between FAST and MeerKAT

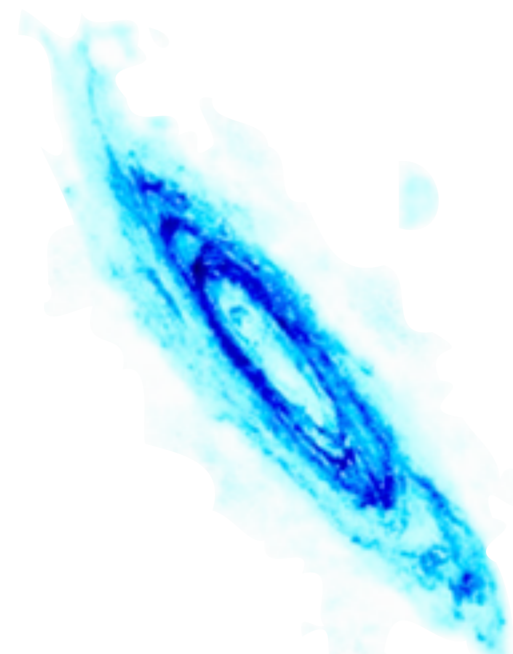


Roger Deane
Danail Obreschkow
Ian Heywood

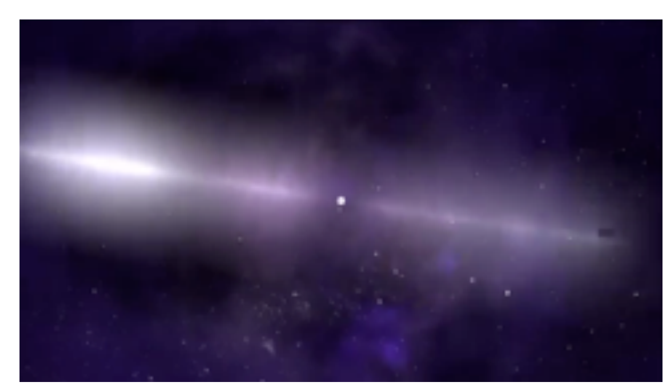


MeerKAT highest priority science

neutral hydrogen



pulsar timing



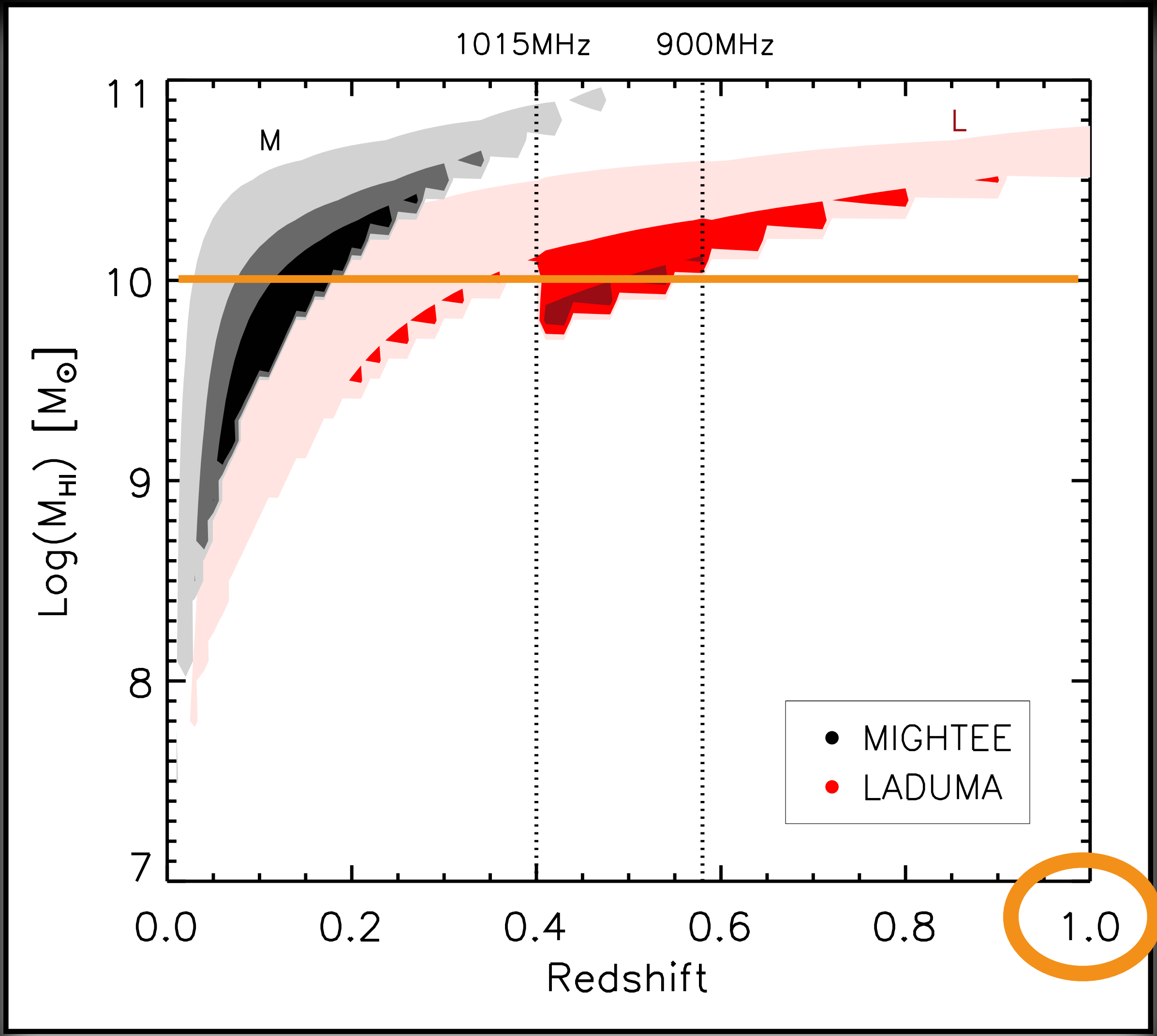
high-z HI emission with MeerKAT

LADUMA

- ~3,500 hours
- 2.5 deg^2 @ z~1
- world-beating measurement of HI mass function at low end for z < 0.58
- ~700 total detections for z > 0.58
- no direct detections of ~10^9 $M_\odot$ systems for z > 0.8

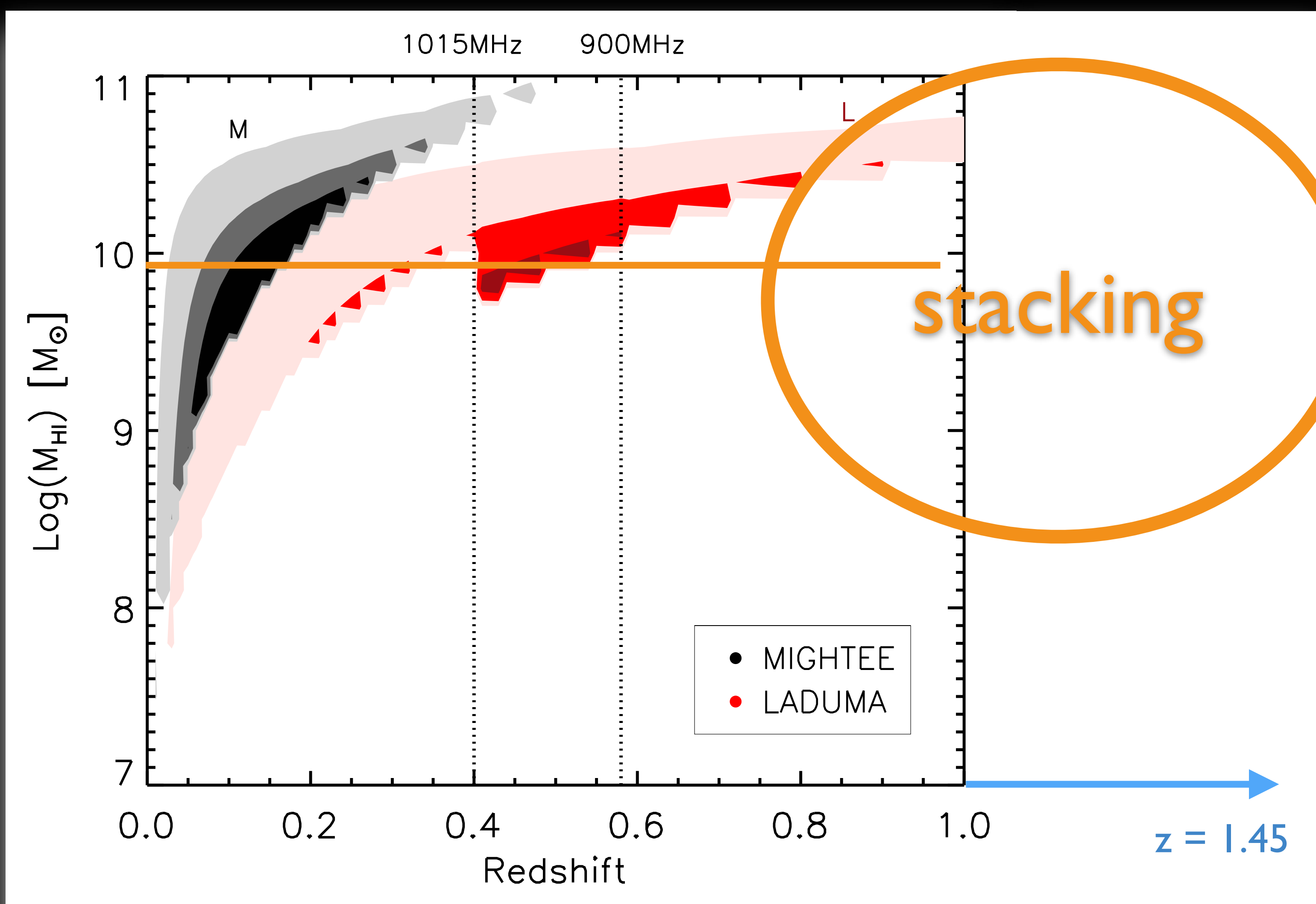
MIGHTEE HI survey

- ~1,800 hours
- ~20 deg^2
- >3000 total detection for z < 0.58
- world-beating measurement of HI mass function at high end for z < 0.58

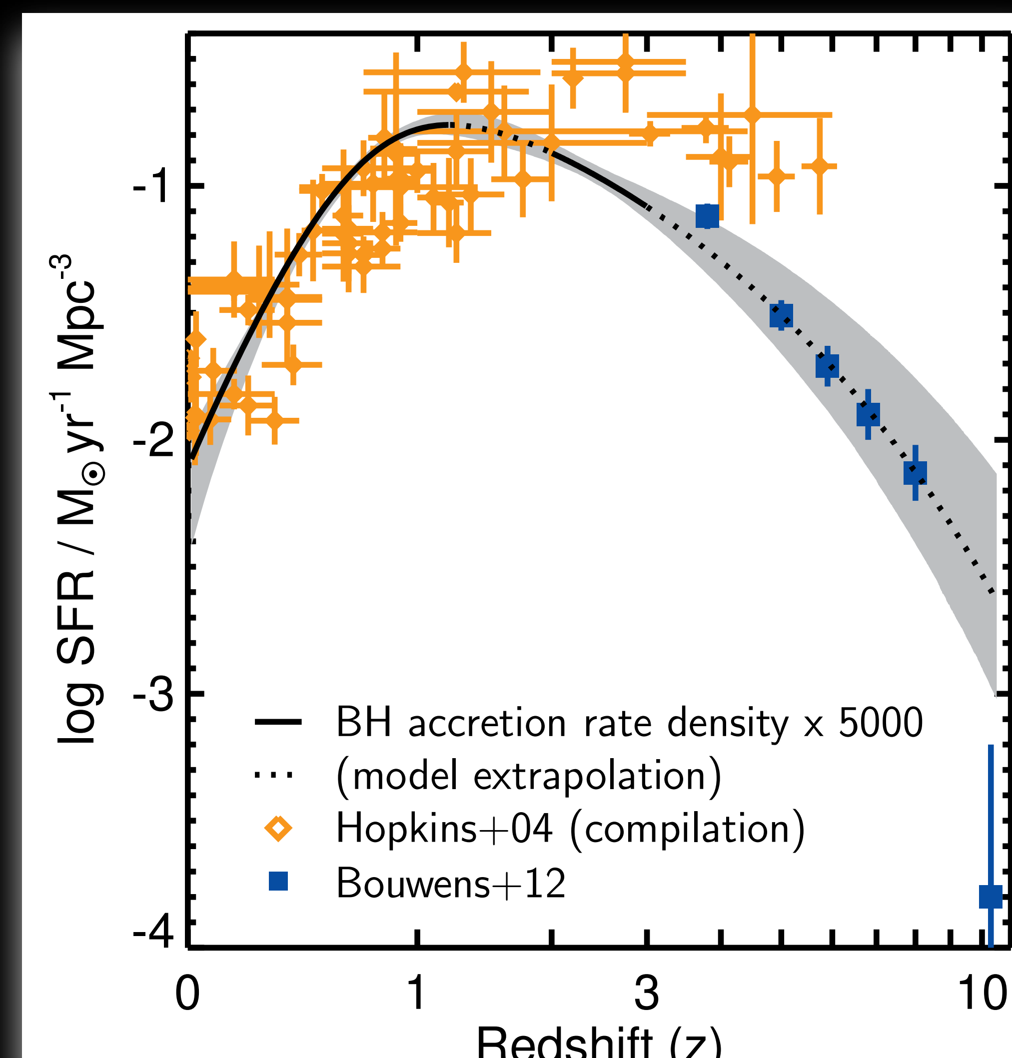


Maddox+2016

high-z HI emission with MeerKAT

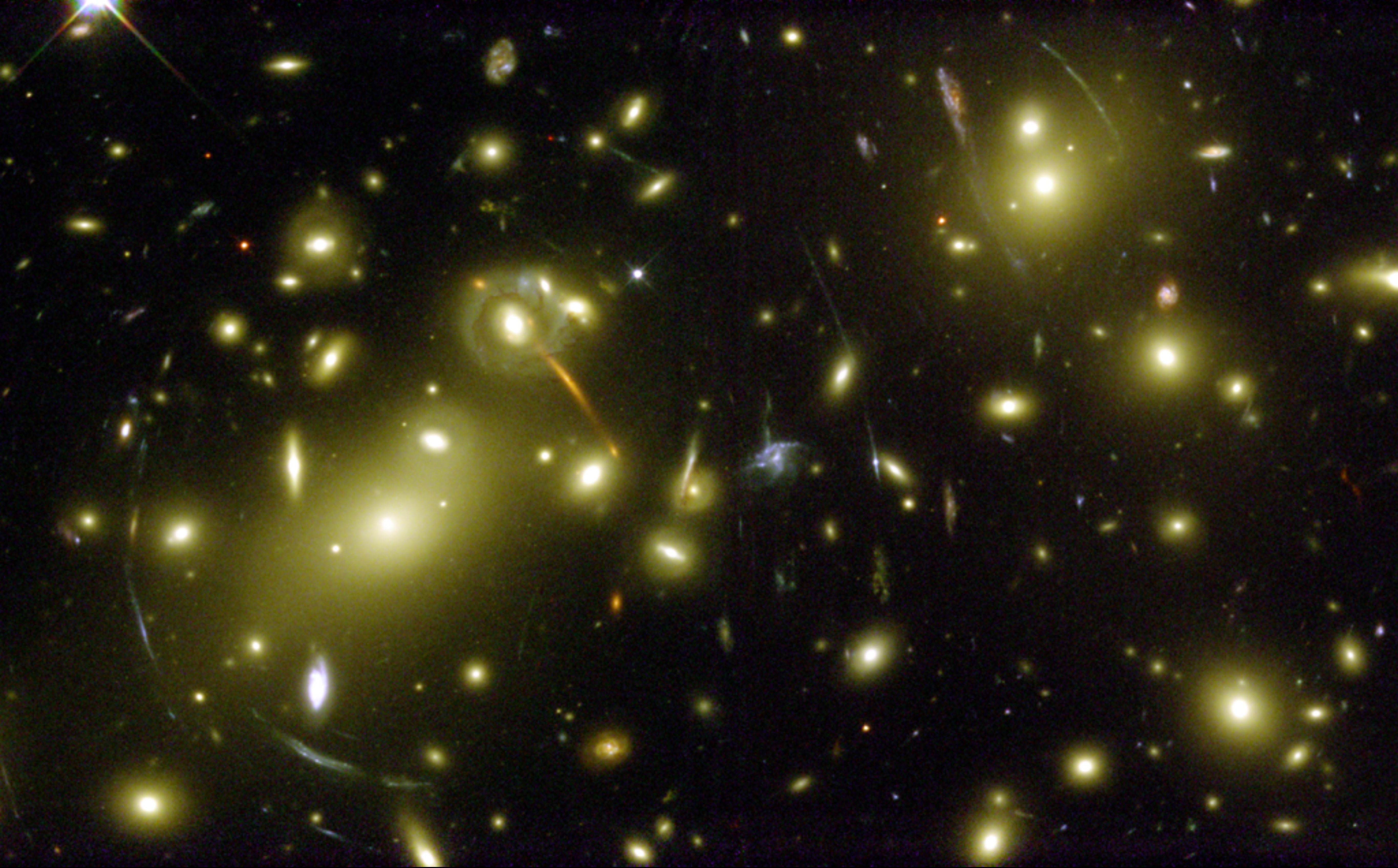


Maddox+2016

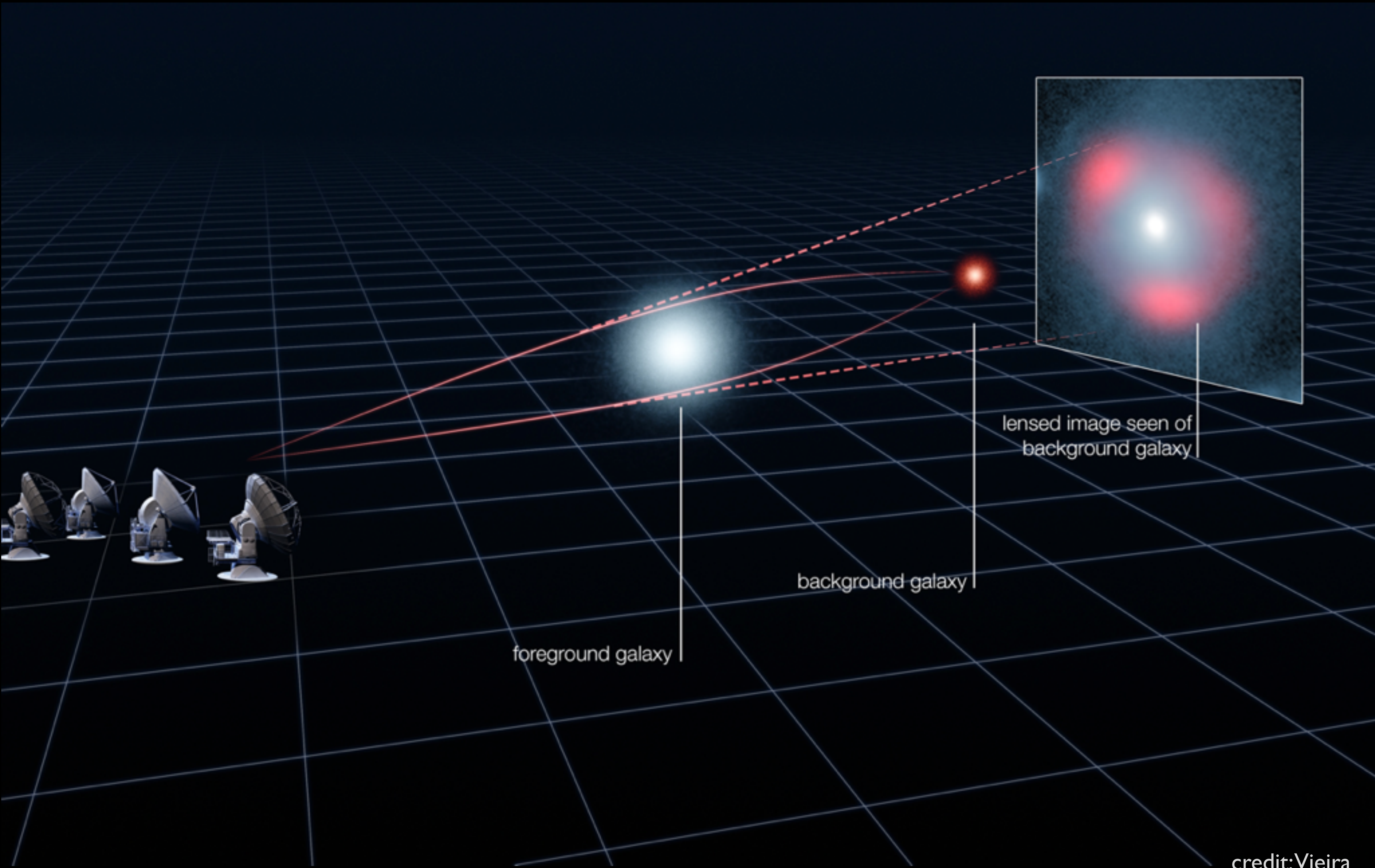


Kormendy & Ho 2013

but with gravitational lensing, MeerKAT and FAST can do even better…

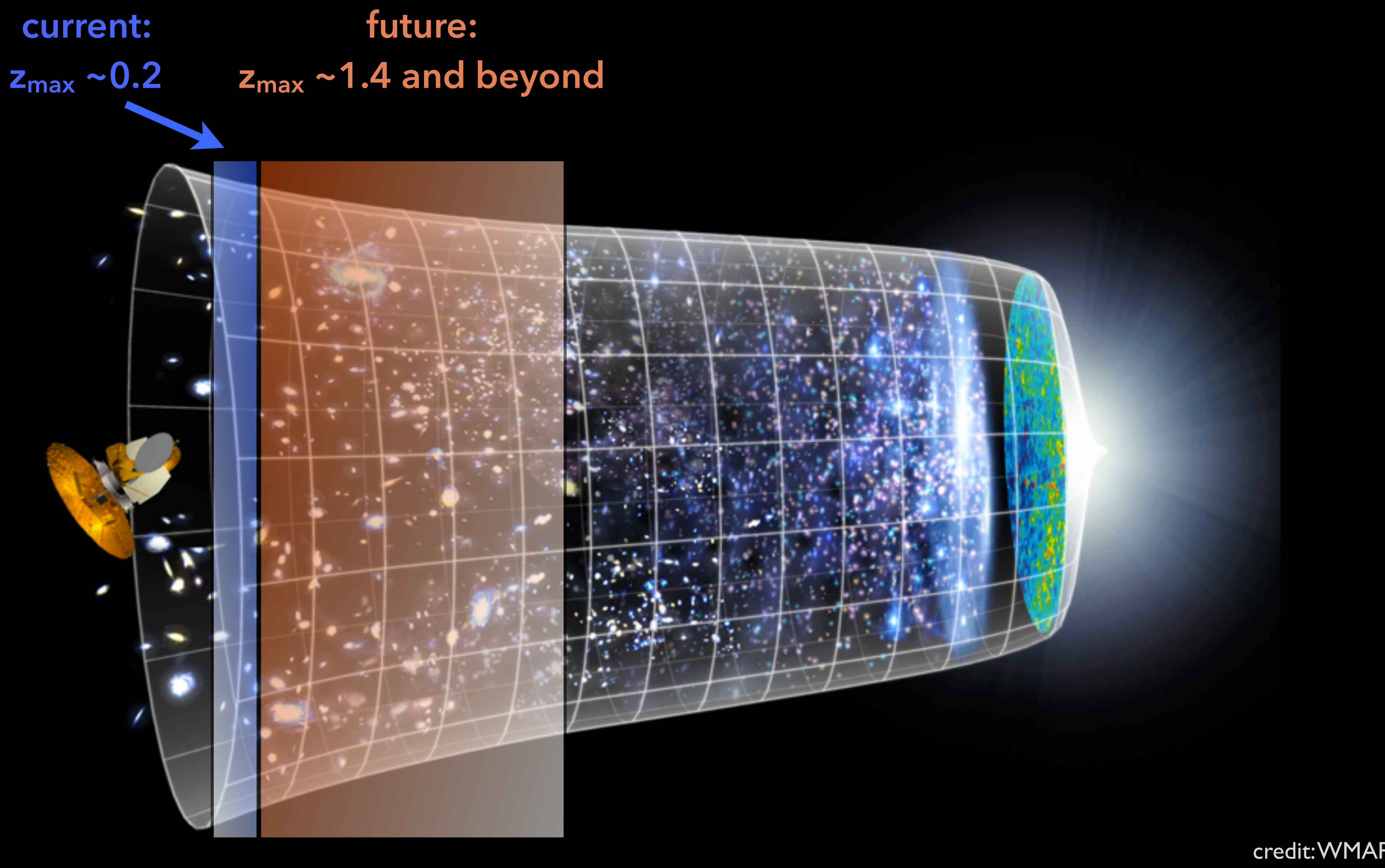


cosmic telescopes

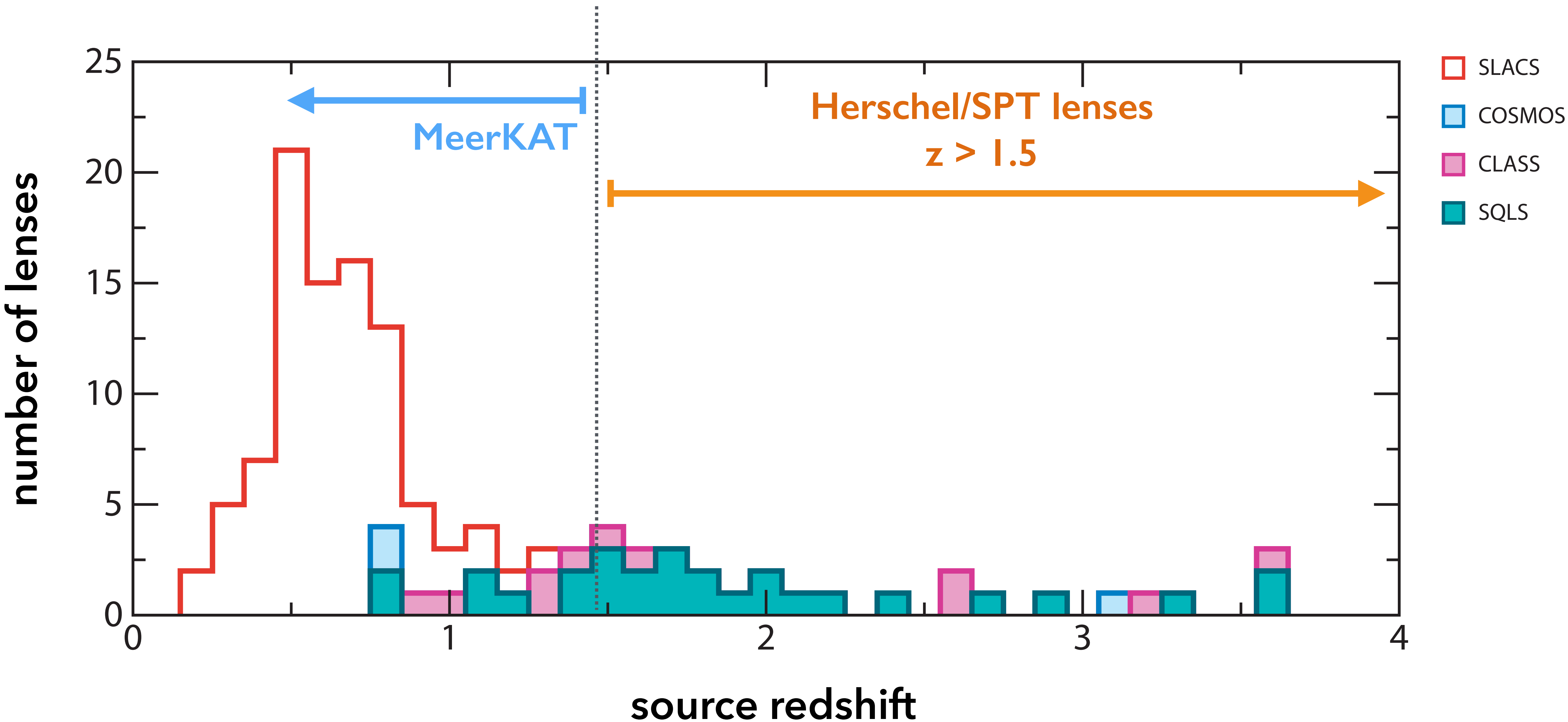


credit: Vieira

HI lensing probability is set dramatically increase for next generation HI surveys



redshift distribution of known lenses

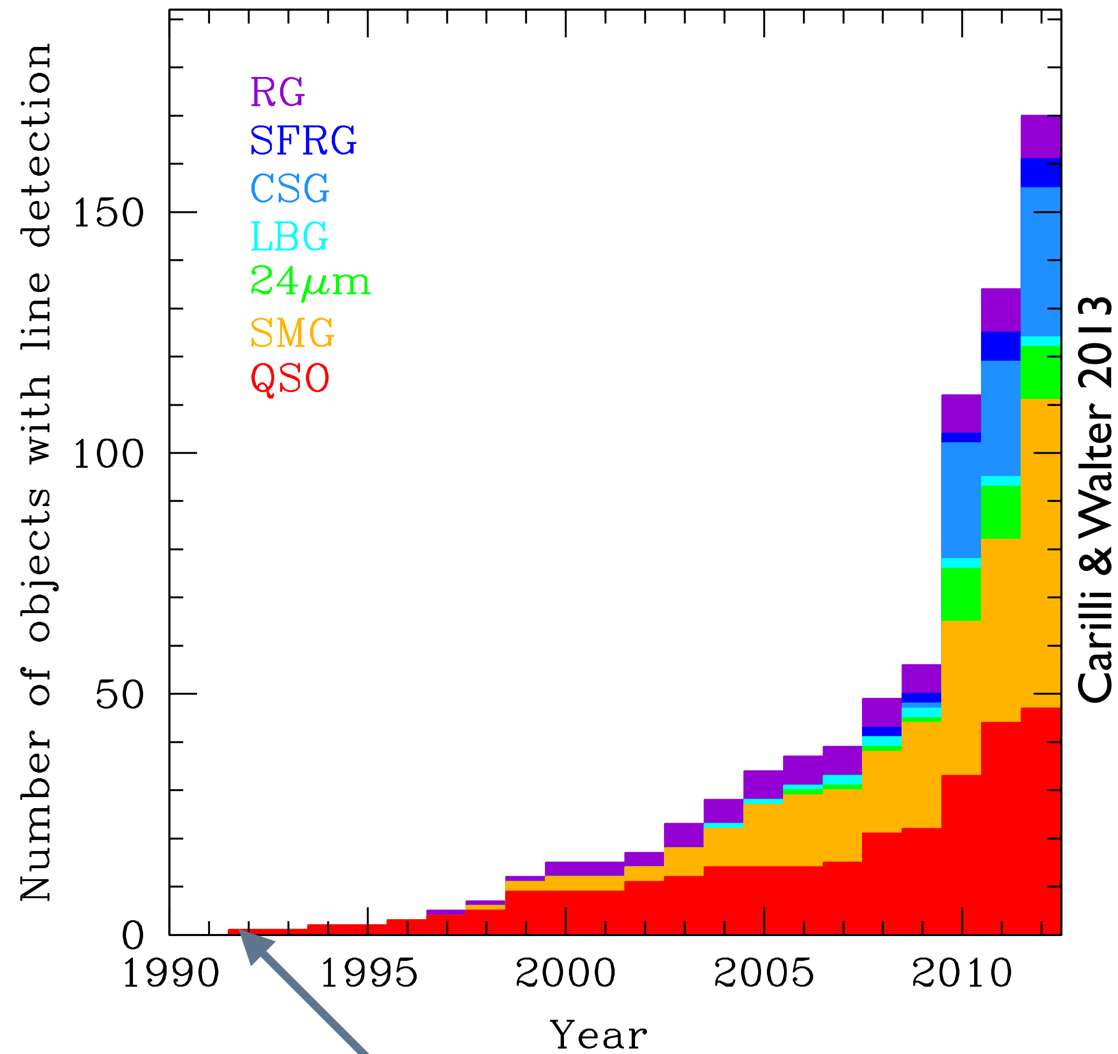


Treu 2010

historical perspective

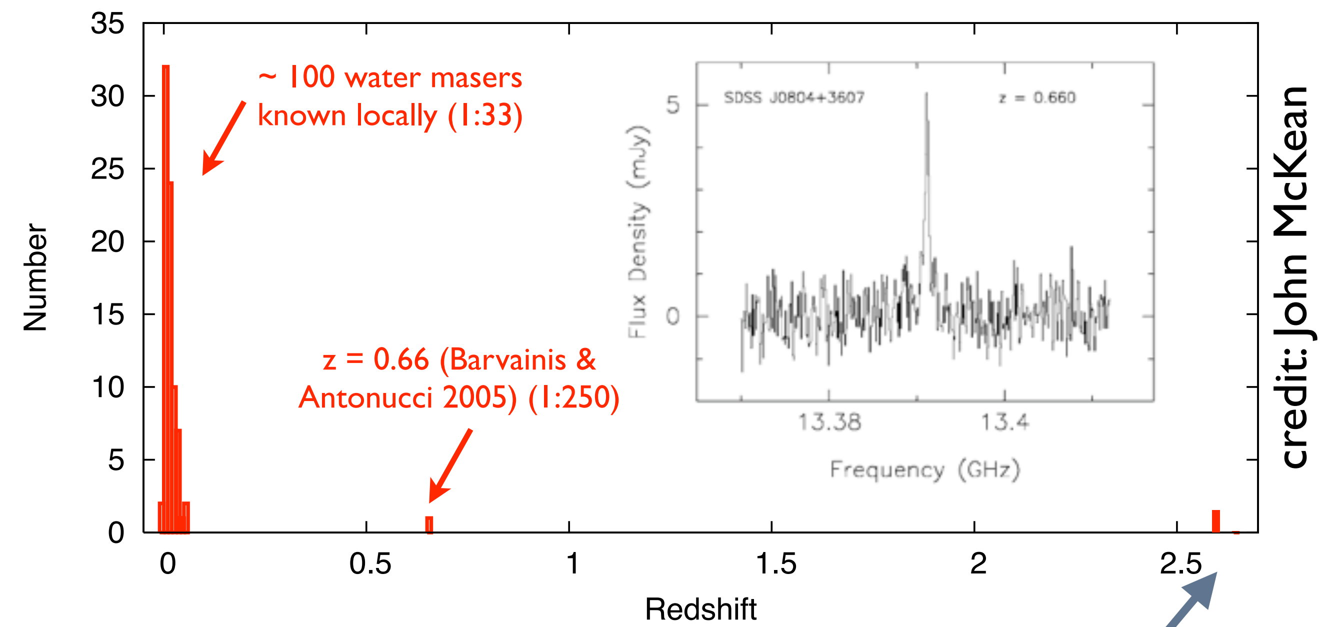
on lensed spectral lines in radio regime

cumulative number of
z >1 CO detections



first detection was a z = 2.3 lensed system!

redshift distribution of
22 GHz **water maser** detections



lensed detection at z = 2.6!

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Strongly lensed neutral hydrogen emission: detection predictions with current and future radio interferometers

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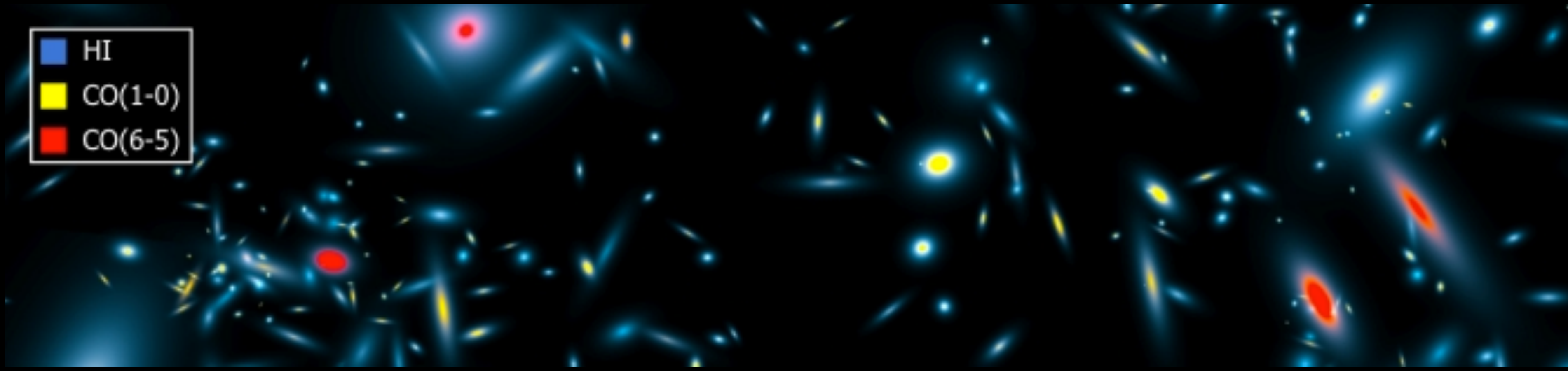
ABSTRACT

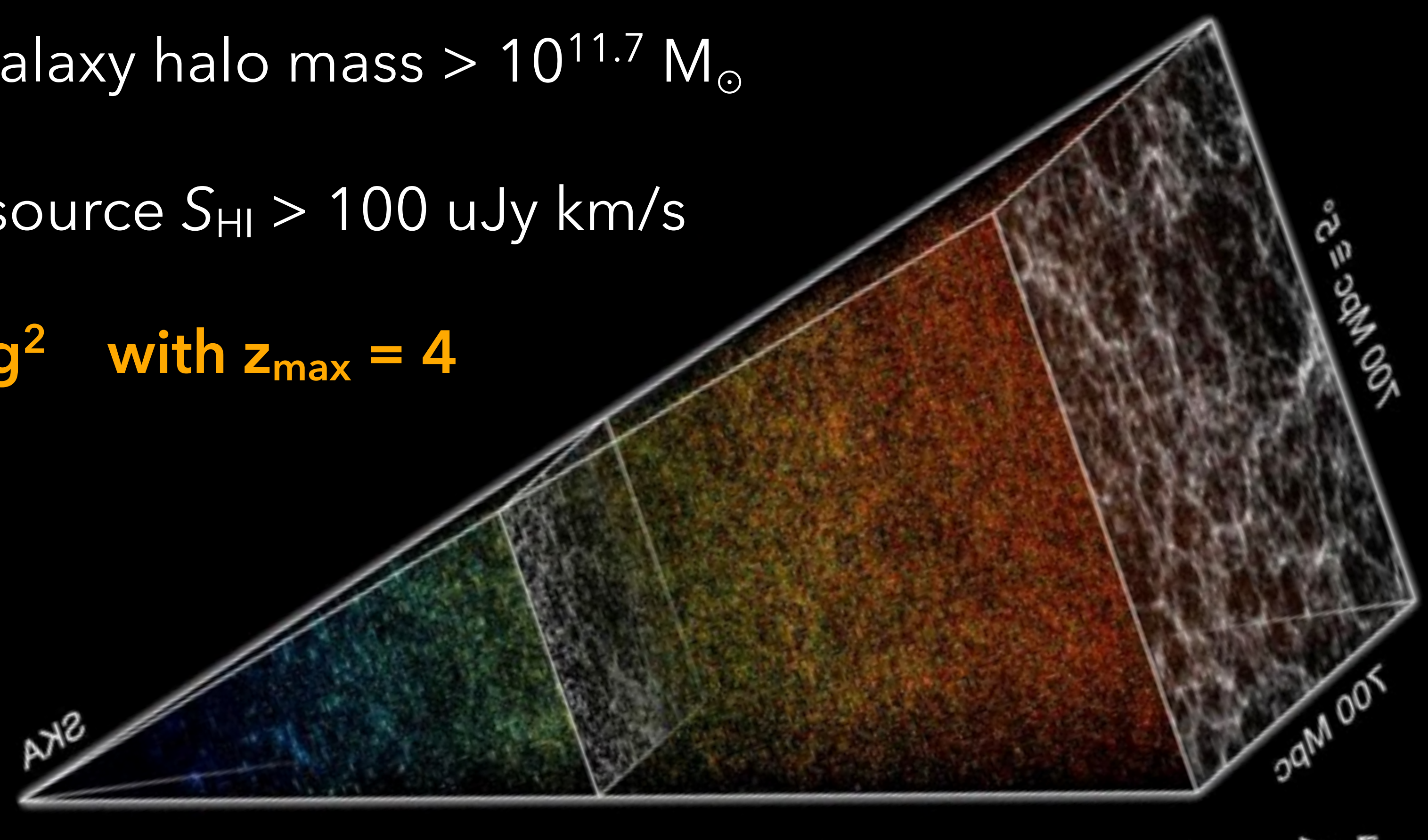
Strong gravitational lensing provides some of the deepest views of the Universe, enabling studies of high-redshift galaxies only possible with next-generation facilities without the lensing phenomenon. To date, 21-cm radio emission from neutral hydrogen has only been detected directly out to $z \sim 0.2$, limited by the sensitivity and instantaneous bandwidth of current radio telescopes. We discuss how current and future radio interferometers such as the Square Kilometre Array (SKA) will detect lensed H I emission in individual galaxies at high redshift. Our calculations rely on a semi-analytic galaxy simulation with realistic H I discs (by size, density profile and rotation), in a cosmological context, combined with general relativistic ray tracing. Wide-field, blind H I surveys with the SKA are predicted to be efficient at discovering lensed H I systems, increasingly so at $z \gtrsim 2$. This will be enabled by the combination of the magnification boosts, the steepness of the H I luminosity function at the high-mass end, and the fact that the H I spectral line is relatively isolated in frequency. These surveys will simultaneously provide a new technique for foreground lens selection and yield the highest redshift H I emission detections. More near term (and existing) cm-wave facilities will push the high-redshift H I envelope through targeted surveys of known lenses.

Key words: gravitational lensing: strong – galaxies: evolution – galaxies: ISM.

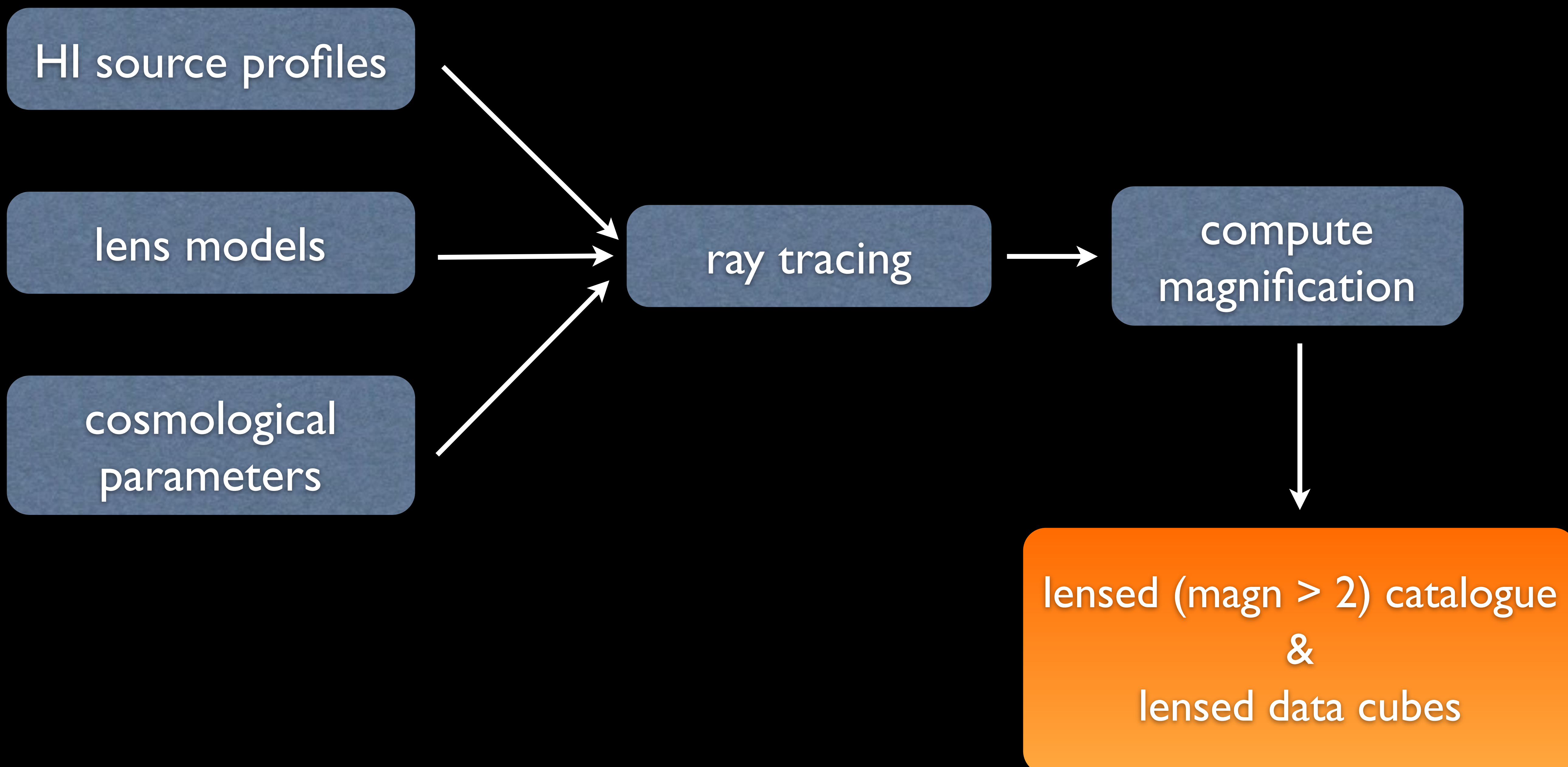
SAXLENS



- SAX - semi-analytics built on Millennium dark matter skeleton
- find all galaxy pairs where:
    - impact parameter < 20 arcsec
    - foreground galaxy halo mass > $10^{11.7}$ $M_\odot$
    - background source S_{HI} > 100 uJy km/s
    - **area: 150 deg^2 with z_{max} = 4**



SAXLENS pipeline

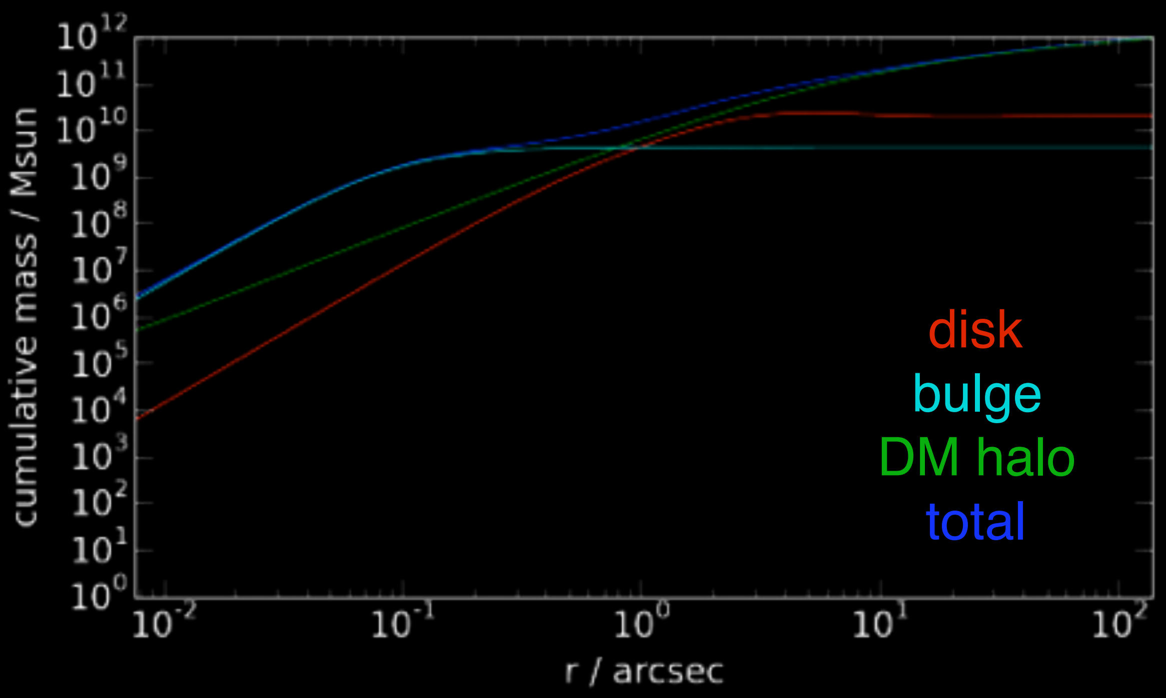


lens models

dark matter halo : spherical NFW profile, concentration parm set given mass and redshift (Klypin+2011)

bulge : de Vaucoleurs' profile, effective radius from dynamical model ellipticity = 0.3 ± 0.3 (Jorgensen & Franx 1994, Moller+2007).

disk : fit to exponential profile. Sub-dominant at all radii, but included as it increases overall convergence.



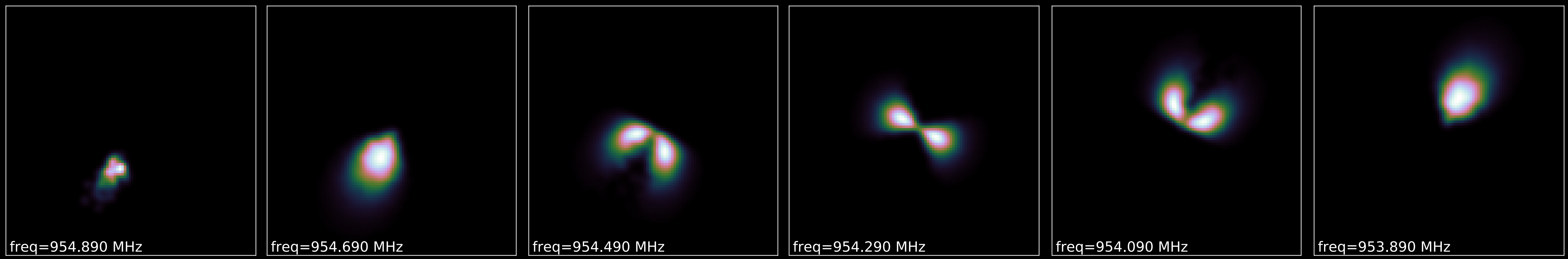
source models

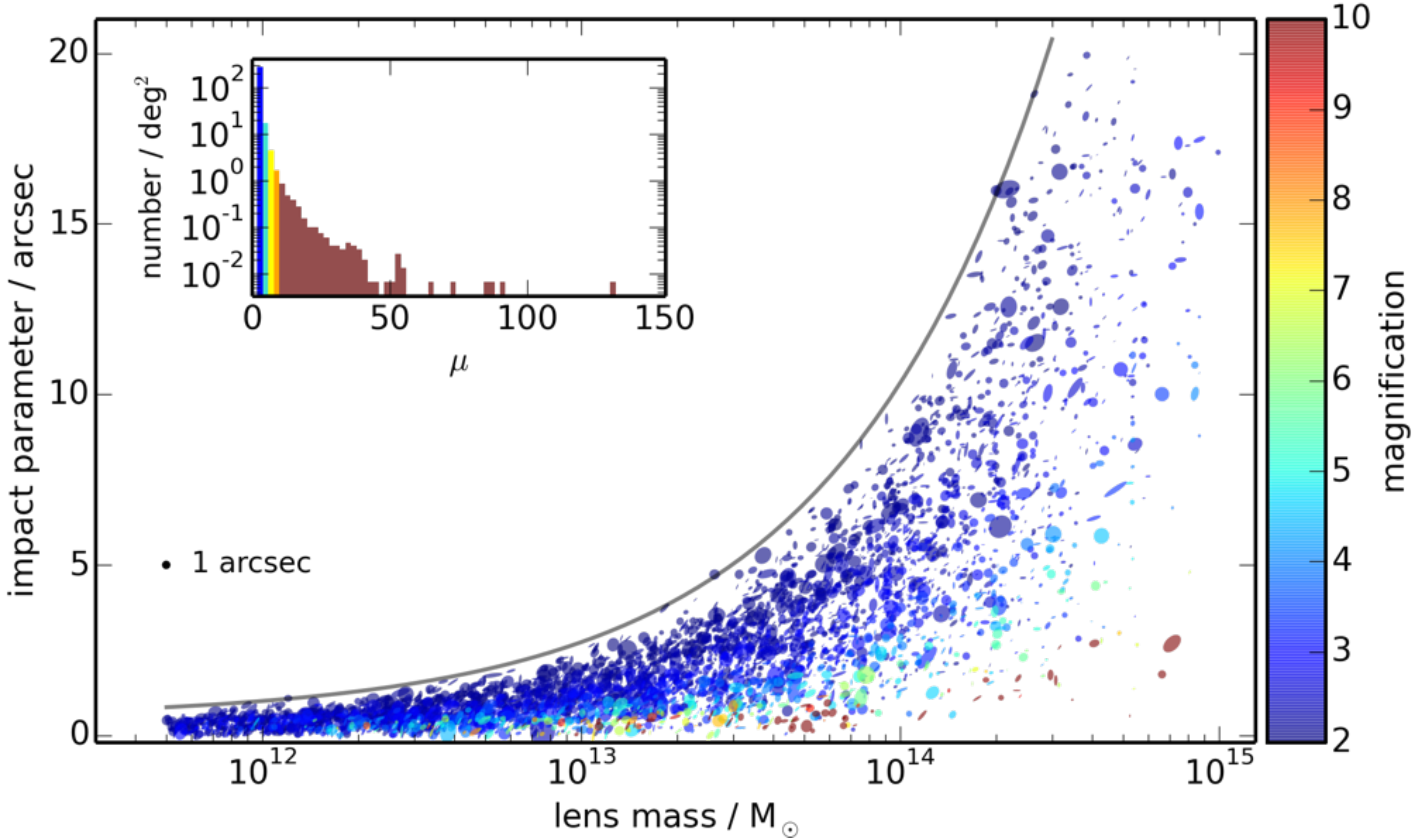
exponential disk with depleted core (Obreschkow+2009). Note, this decreases total magnification

randomised inclination and position angle from simulation

emission split into frequency channels velocity dispersion added (10 km/s)

example HI disk at z~0.5, 200 kHz channels



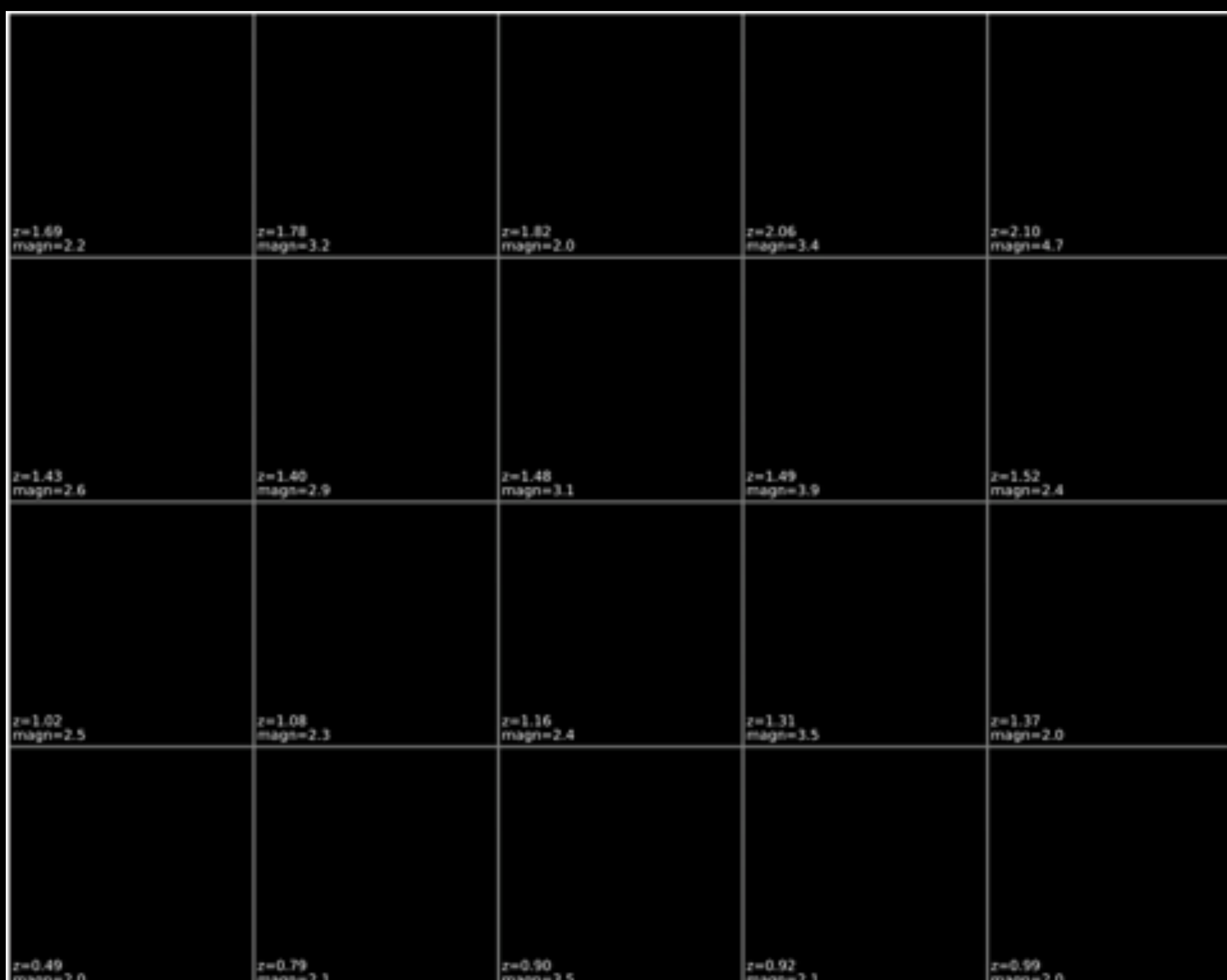


impact parameter / arcsec
lens mass / M$_\odot$
magnification
number / deg^2
μ
1 arcsec
0
5
10
15
20
10^{12}
10^{13}
10^{14}
10^{15}
2
3
4
5
6
7
8
9
10
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
0
50
100
150

200 kHz channel maps

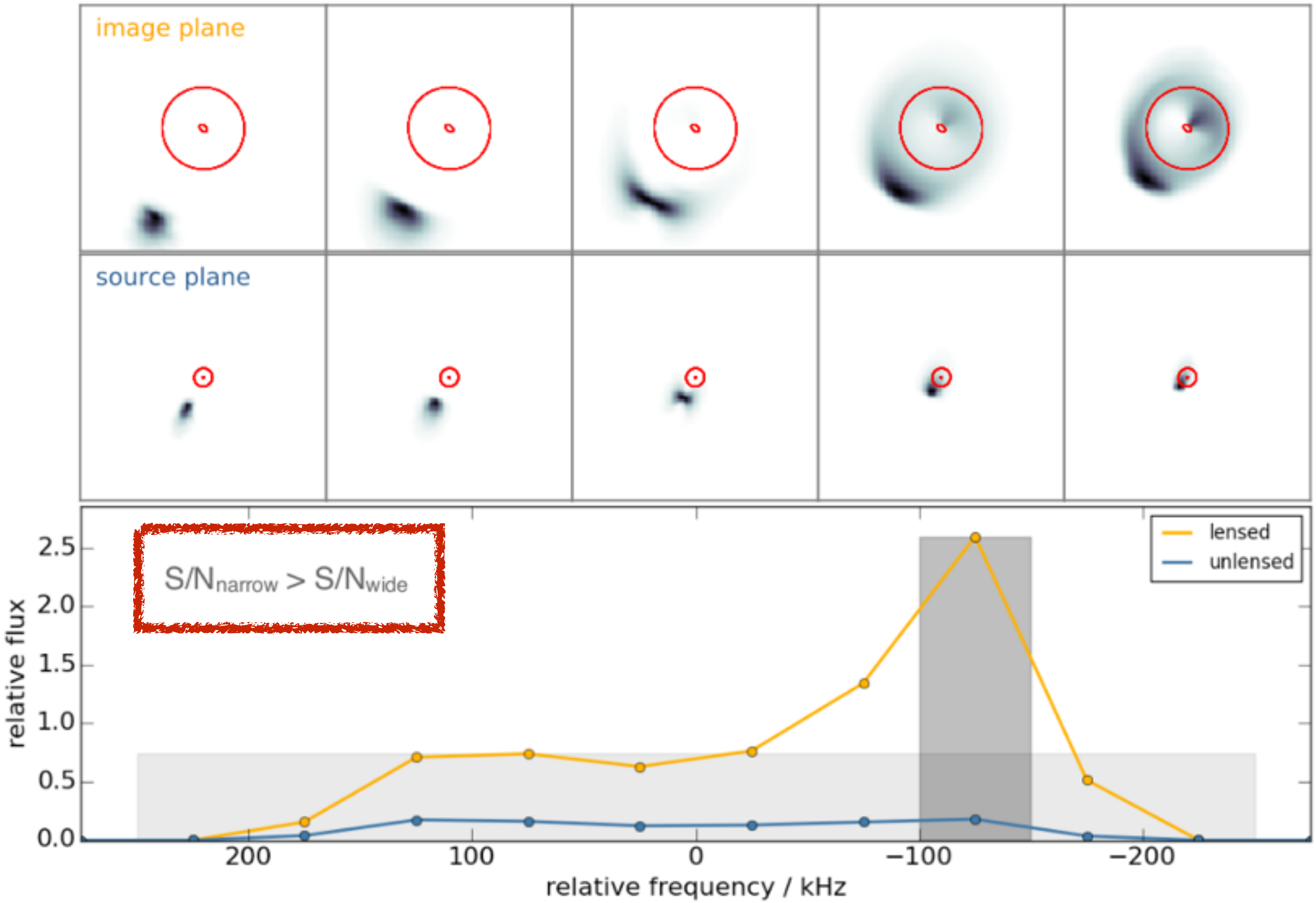
(HST resolution)

unlensed



MeerKAT angular resolution well matched to lensed HI sources: maximises detection probability

high magnification narrow channels



lensed HI predictions for future HI surveys

Survey	Ω deg^2	σ_{100kHz} μJy/b	z_{max}	N_{detect}	$\bar{z}_{\mathrm{detect}}$
CHILES	0.25	20	0.45	< 0.1	0.35
LADUMA	0.60	8	1.45	20 (47)	0.96
DINGO-UD	60	38	0.43	3 (8)	0.30
DINGO-D	150	85	0.26	1 (2)	0.16
SKA1-Deep	100	10	3.06	2,880 (7,265)	1.26
SKA1-MedDeep	1,000	33	3.06	2,480 (7,193)	1.19
SKA1-Wide	10,000	100	3.06	2,667 (7,467)	0.93

lensed HI opportunities with MeerKAT

PROCEEDINGS OF SCIENCE

Gravitationally Lensed H I with MeerKAT

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The SKA era is set to revolutionize our understanding of neutral hydrogen (H I) in individual galaxies out to redshifts of $z \sim 0.8$; and in the $z > 6$ intergalactic medium through the detection and imaging of cosmic reionization. Direct H I number density constraints will, nonetheless, remain relatively weak out to cosmic noon ($z \sim 2$) - the epoch of peak star formation and black hole accretion - and beyond. However, as was demonstrated from the 1990s with molecular line observations, this can be overcome by utilising the natural amplification afforded by strong gravitational lensing, which results in an effective increase in integration time by a factor of μ^2 for an unresolved source. Here we outline how a dedicated lensed H I survey will leverage MeerKAT's high sensitivity, frequency coverage, large instantaneous bandwidth, and high dynamic range imaging to enable a lasting legacy of high-redshift H I emission detections well into the SKA era. This survey will not only provide high-impact, rapid-turnaround MeerKAT science commissioning results, but also unveil Milky Way-like systems towards cosmic noon which is not possible with any other SKA precursors/pathfinders. An ambitious lensed H I survey will therefore make a significant impact from MeerKAT commissioning all the way through to the full SKA era, and provide a more complete picture of the H I history of the Universe.

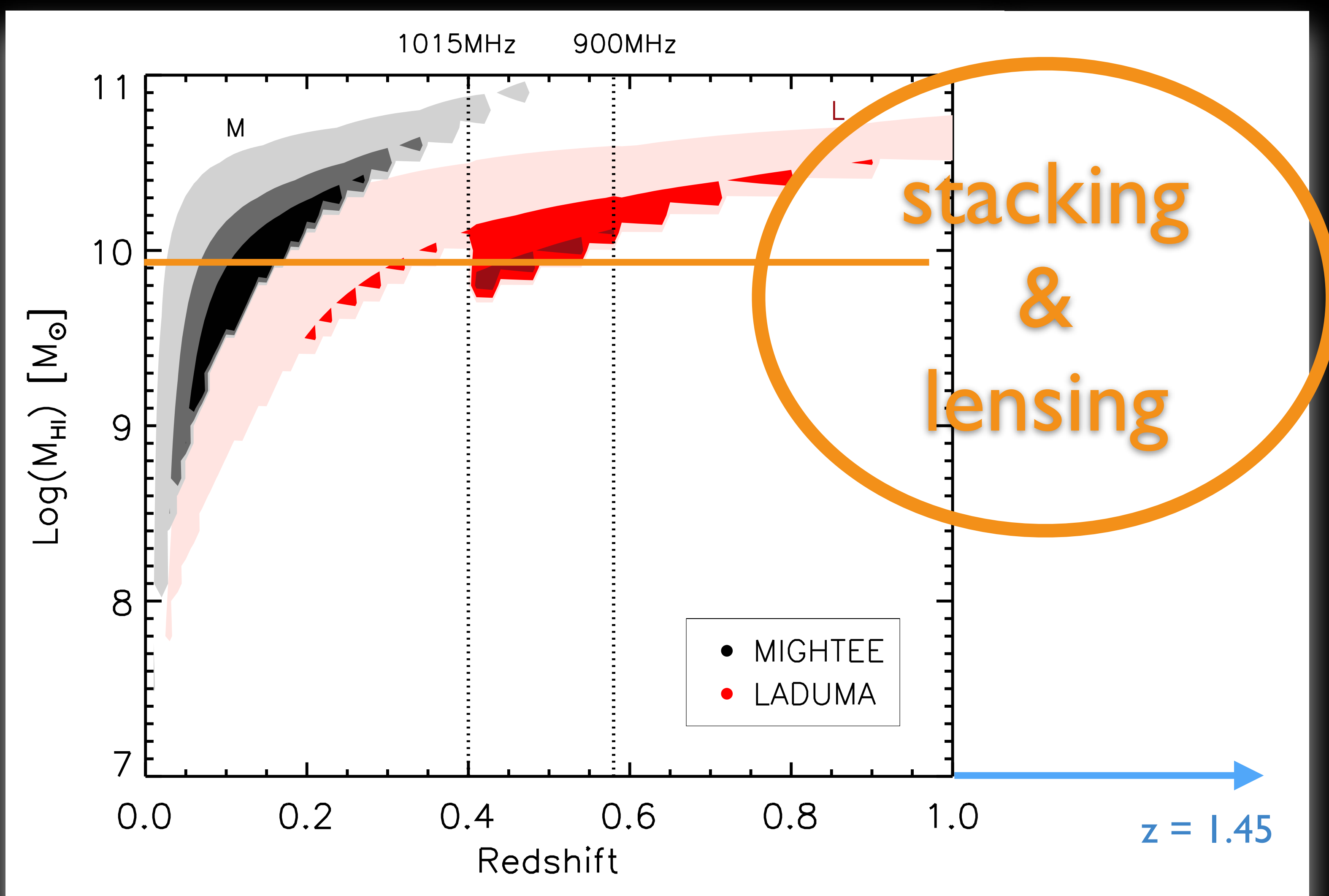
why is MeerKAT well-suited?

- most sensitive interferometer pre-SKA for $z_{HI} < 1.45$
- well-matched angular resolution
- wide instantaneous bandwidth
- wide field-of-view
- high imaging dynamic range
- excellent low-RFI site (even better in UHF band)

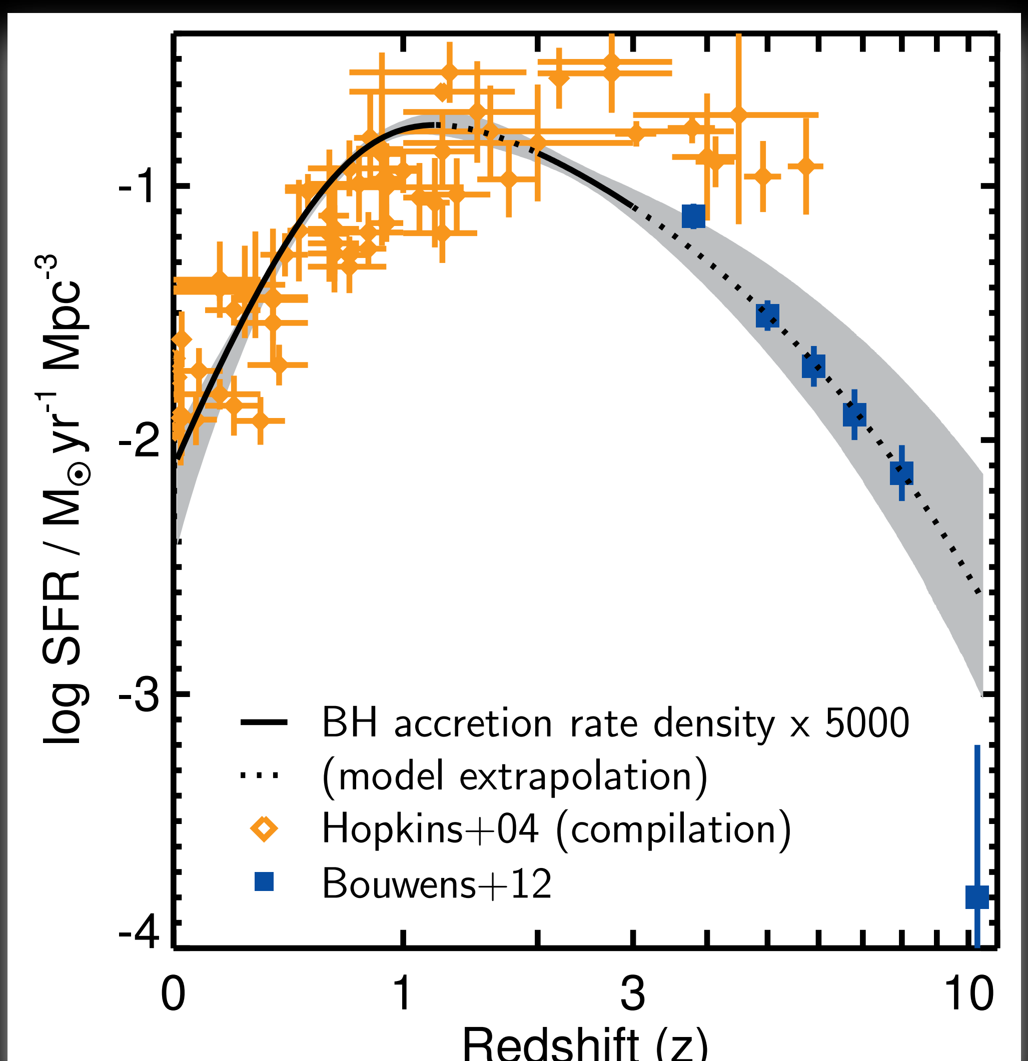
what do lenses offer?

- highest redshift detections of lensed HI emission in galaxies
- low mass detections at cosmological distances
- unique lens selection
- high impact early science
- guidance to future SKA1-mid surveys

high-z HI emission with MeerKAT



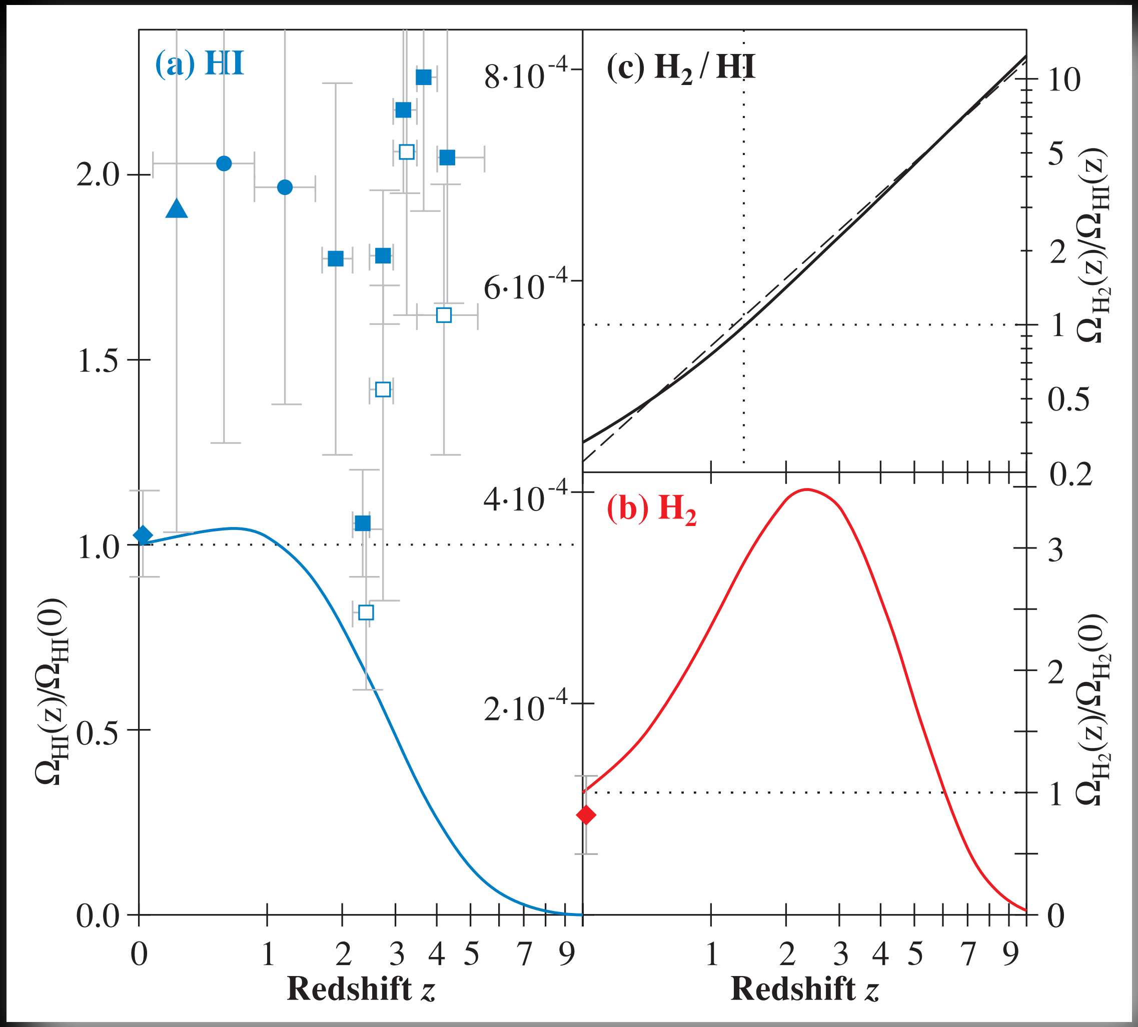
Maddox+2016



Kormendy & Ho 2013

H_2-to-HI mass ratio at z > 1

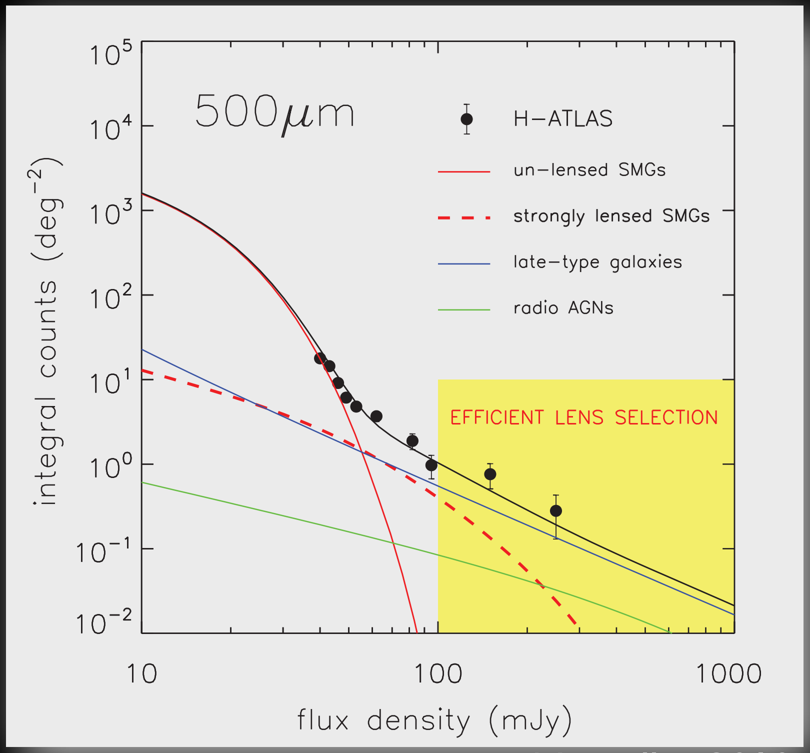
- detection of z~1.5 systems in low-*J* CO now routine
- to measure H_2-to-HI ratio towards peak cosmic star formation peak, will need direct detections of HI
- important synergy with ALMA, and lasting legacy towards SKA1-mid



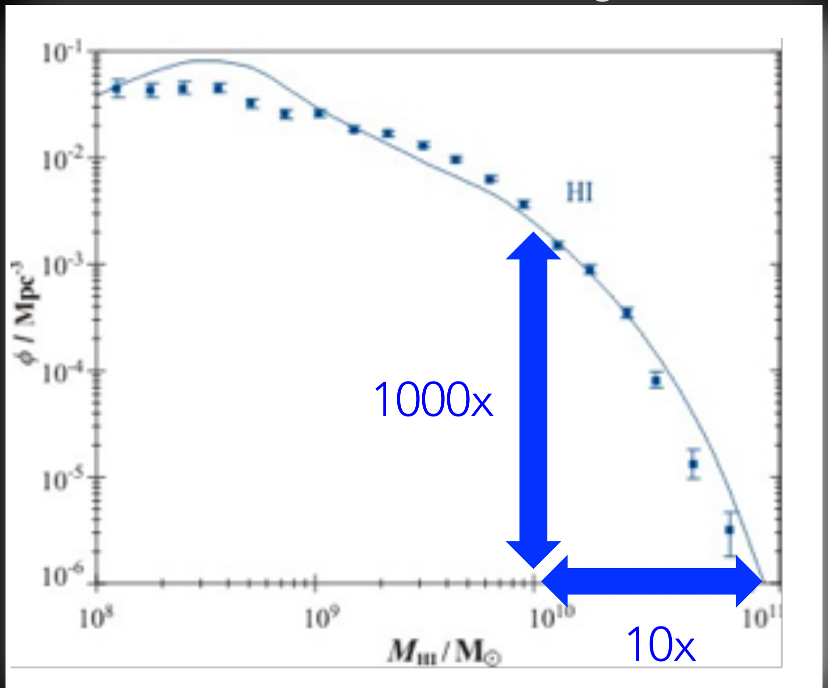
Obreschkow & Rawlings 2009

efficient lens selection with steep luminosity functions

- technique used at submm/mm wavelengths (Herschel, SPT)
- steep gradient at high end enables highly efficient selection
- similar opportunity for HI, but even better given that redshift is known
- no other strong emission lines between 580 and 1420 MHz



Negrello+2010



Obreschkow+2009

(one possible) MeerKAT lensed HI strategy

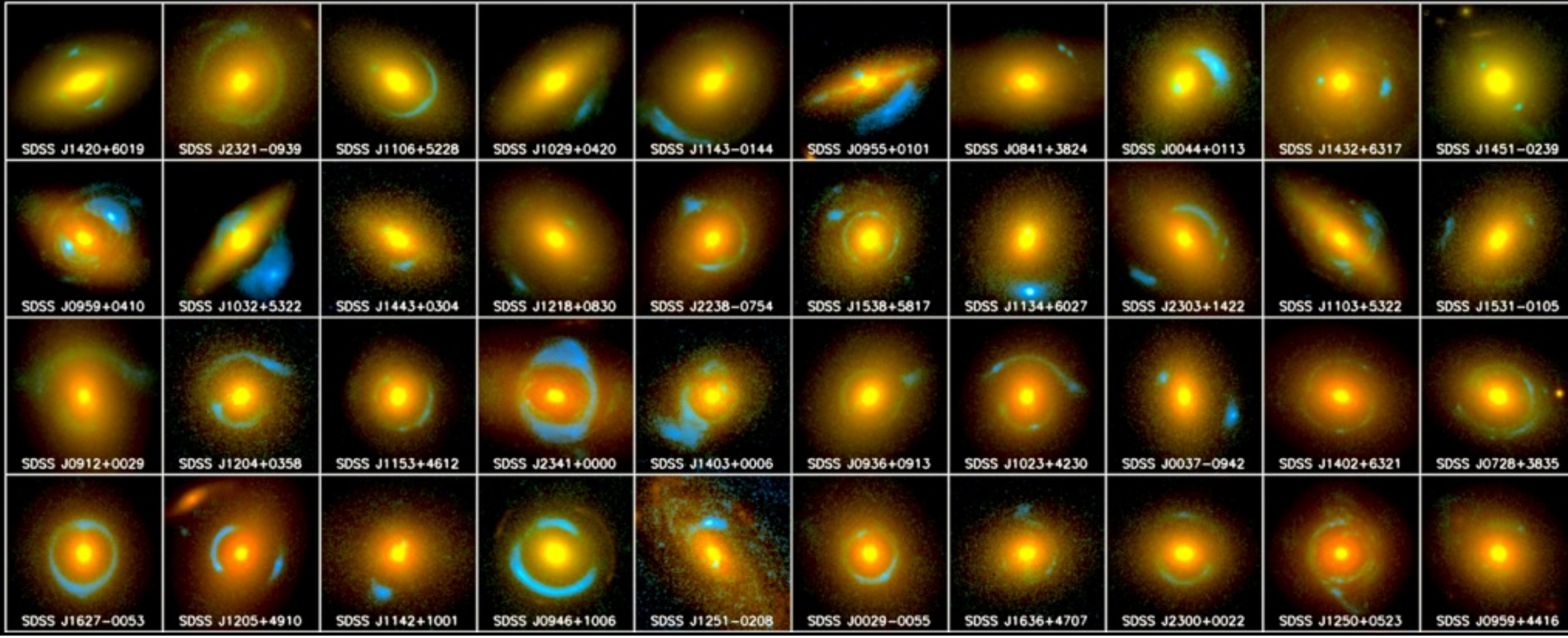
20 known galaxy-galaxy lenses

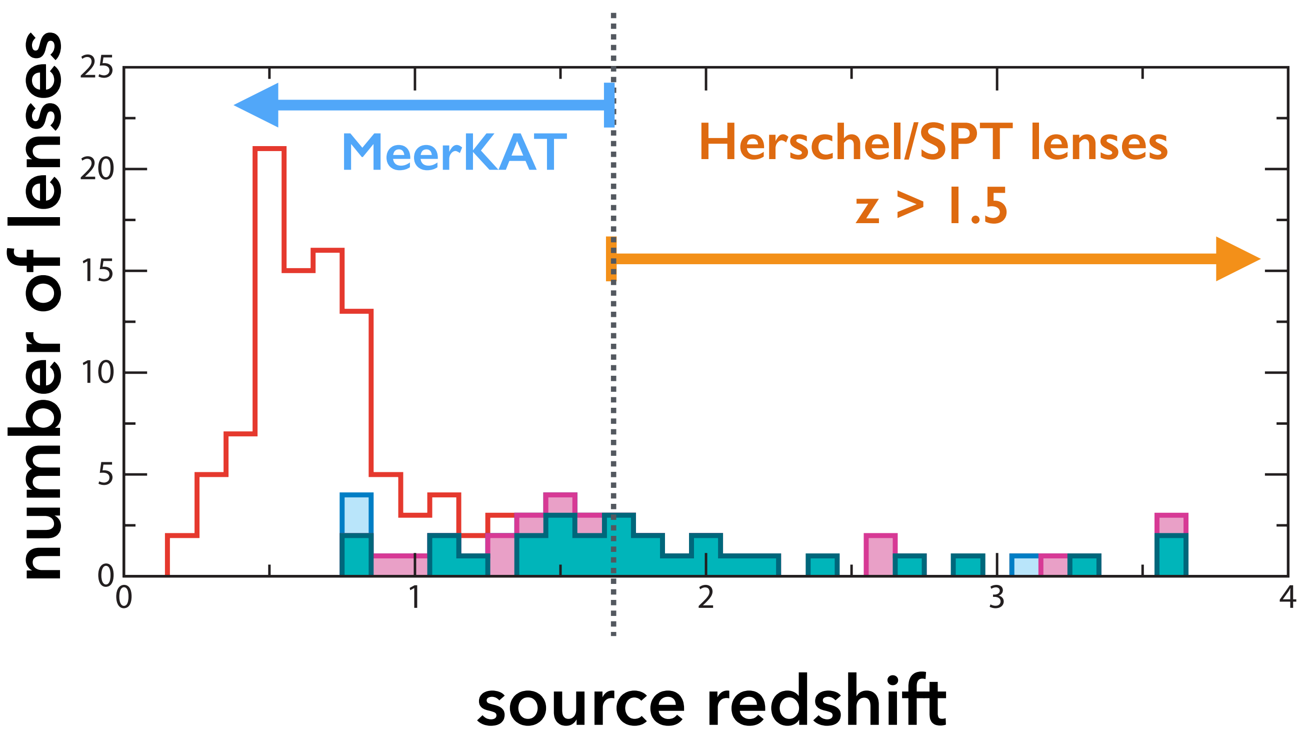
(0.4 < z < 1.4, detections in 10-50 hours)

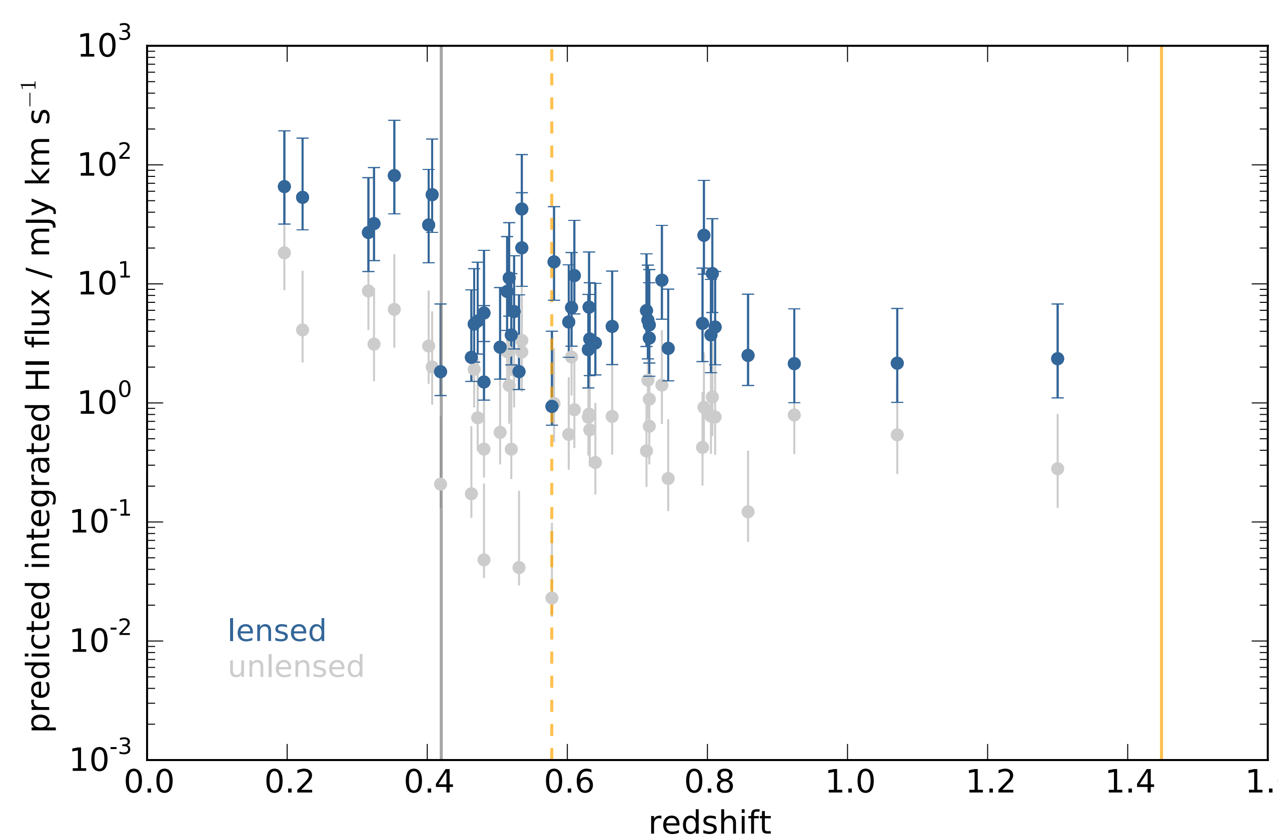
5 clusters for 50 hours (UHF band)

1 cluster for 250 hours (UHF band)

NB: for magnification = 10, the effective observation time is 5000 hours for a 50 hour observation


SDSS J1420+6019
SDSS J2321−0939
SDSS J1106+5228
SDSS J1029+0420
SDSS J1143−0144
SDSS J0955+0101
SDSS J0841+3824
SDSS J0044+0113
SDSS J1432+6317
SDSS J1451−0239
SDSS J0959+0410
SDSS J1032+5322
SDSS J1443+0304
SDSS J1218+0830
SDSS J2238−0754
SDSS J1538+5817
SDSS J1134+6027
SDSS J2303+1422
SDSS J1103+5322
SDSS J1531−0105
SDSS J0912+0029
SDSS J1204+0358
SDSS J1153+4612
SDSS J2341+0000
SDSS J1403+0006
SDSS J0936+0913
SDSS J1023+4230
SDSS J0037−0942
SDSS J1402+6321
SDSS J0728+3835
SDSS J1627−0053
SDSS J1205+4910
SDSS J1142+1001
SDSS J0946+1006
SDSS J1251−0208
SDSS J0029−0055
SDSS J1636+4707
SDSS J2300+0022
SDSS J1250+0523
SDSS J0959+4416


number of lenses
MeerKAT
Herschel/SPT lenses
z > 1.5
source redshift


predicted integrated HI flux / mJy km s^{-1}
redshift
lensed
unlensed

Treu 2010

MeerKAT and FAST synergies for lensed HI

- $z_{HI} < 1.45$
- (A/T_{sys}) ~ 300 m^2/K
- survey speed: (A/T_{sys}) x FoV ~ 300 $m^2/K\ deg^2$
- angular resolution ~10″

- z_{HI} ~< 4
- (A/T_{sys}) ~ 2000 m^2/K
- survey speed: (A/T_{sys}) x FoV ~ 5 $m^2/K\ deg^2$
- angular resolution ~180″

Abell 370 (Hubble Frontier Field)

$z = 0.375$

Dec = -01:35:00

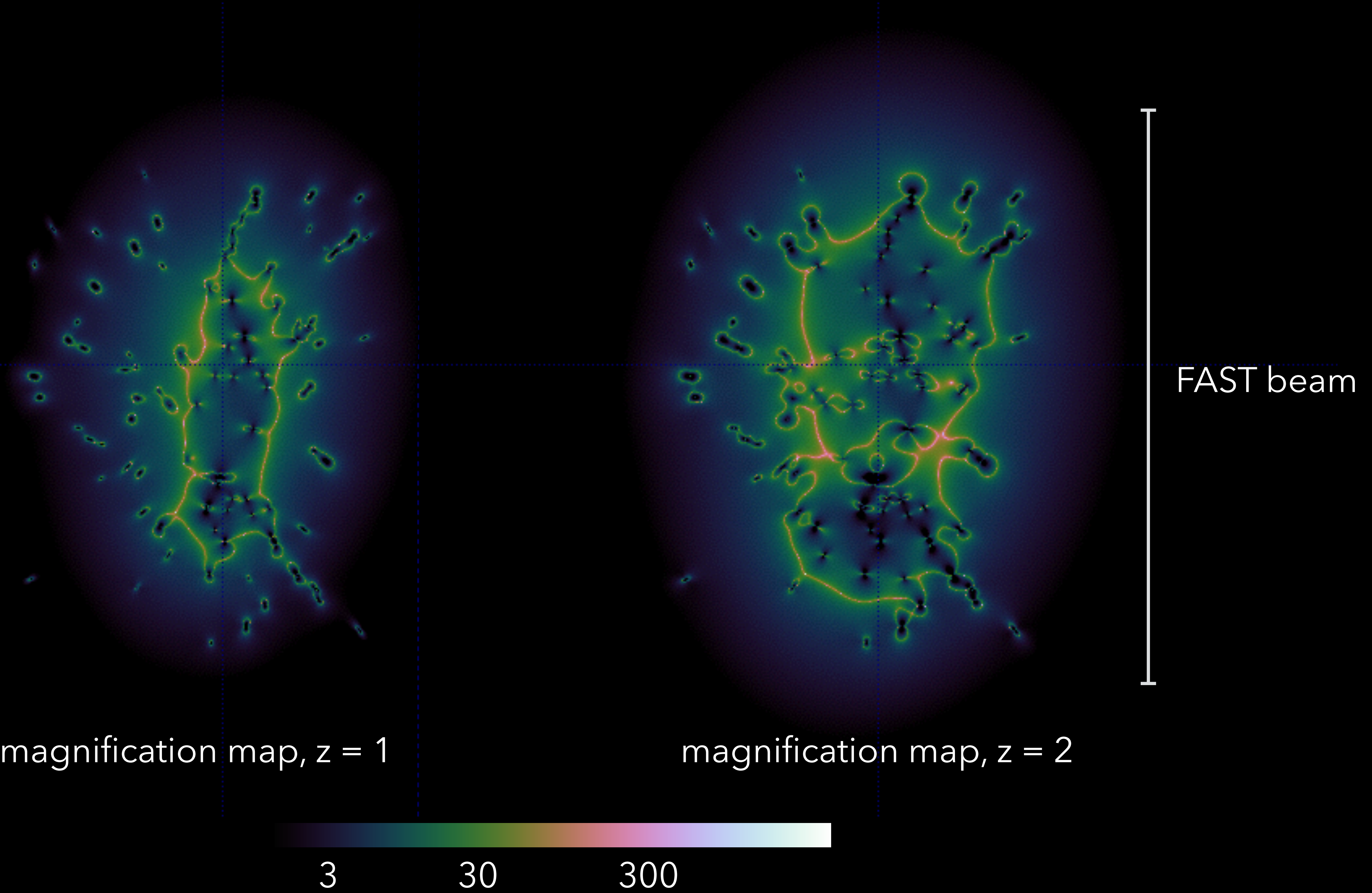
Galaxy Cluster Abell 370
Hubble Space Telescope ▪ ACS/WFC

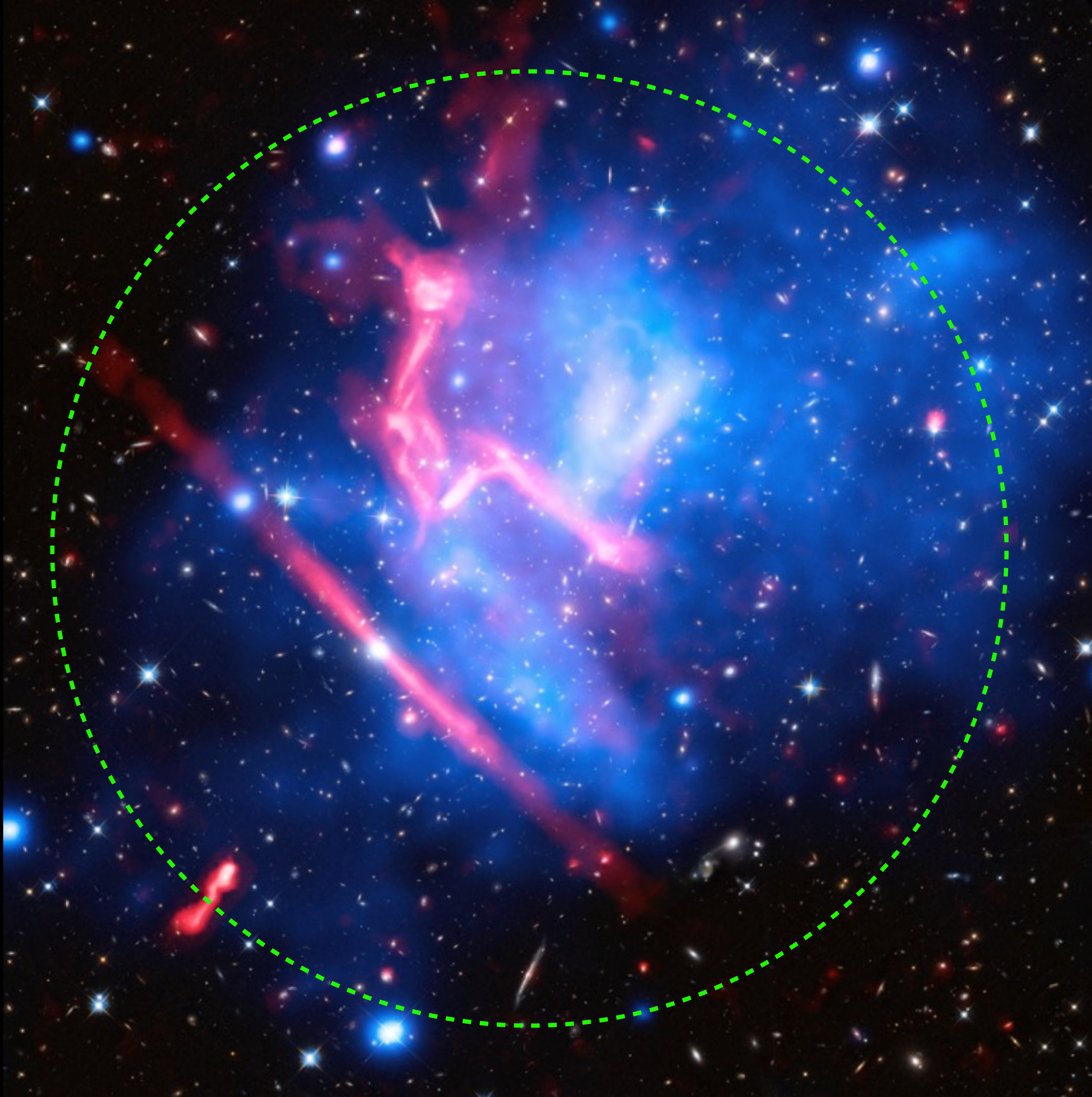
NASA, ESA, the Hubble SM4 ERO Team, and ST-ECF STScI-PRC09-25h

Abell 370 (Hubble Frontier Field)

z = 0.375

Dec = -01:35:00





FAST beam

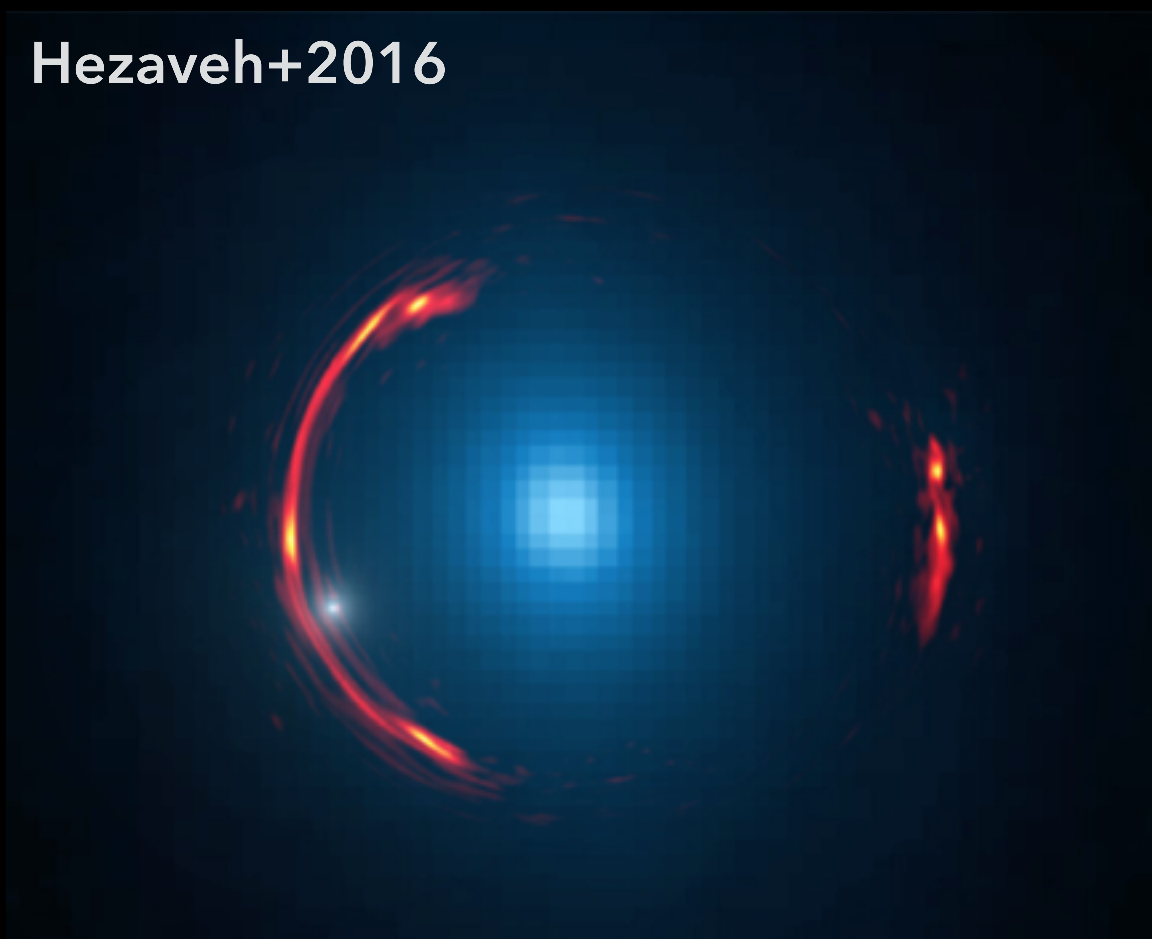
MeerKAT PSF

MACS J0707

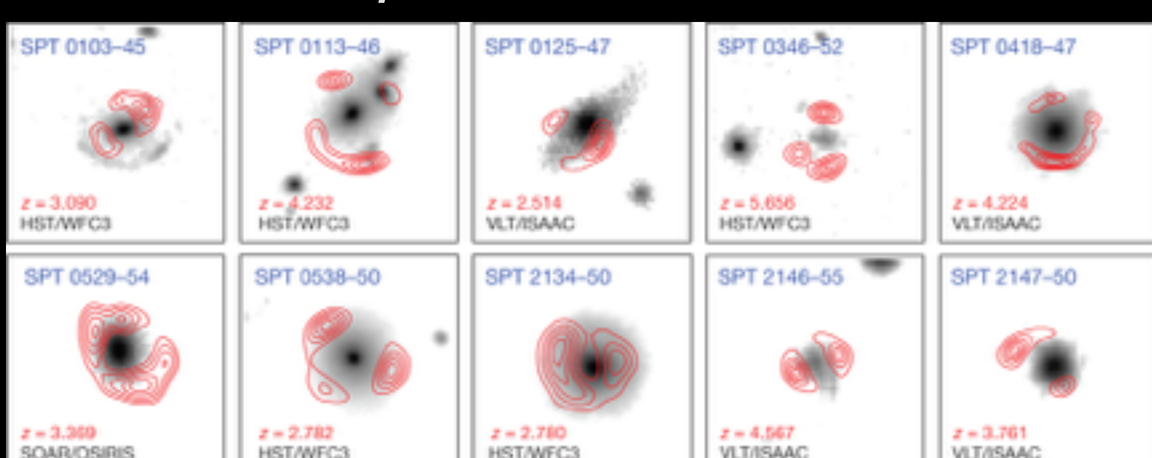
van Weeren et al. (2016)

high impact early science

(c.f. ALMA/SPT, Herschel)



Vieira+ 2013, *Nature*



lenses have been a major part of early science for a range of new observatories/surveys

MeerKAT and FAST have the same opportunity with HI

summary

- **MeerKAT and FAST** will (emphatically) be the **best facilities to detect lensed HI pre-SKA** and likely be highly synergistic
- a dedicated HI lensing programme will provide **high-impact, rapid-turnaround early science**
- **important cross-checks** with stacking/statistical methods
- significantly lower risk on calibration for high-z HI
- **high legacy value** well into SKA era