Cosmology with SKA Square Kilometer Array

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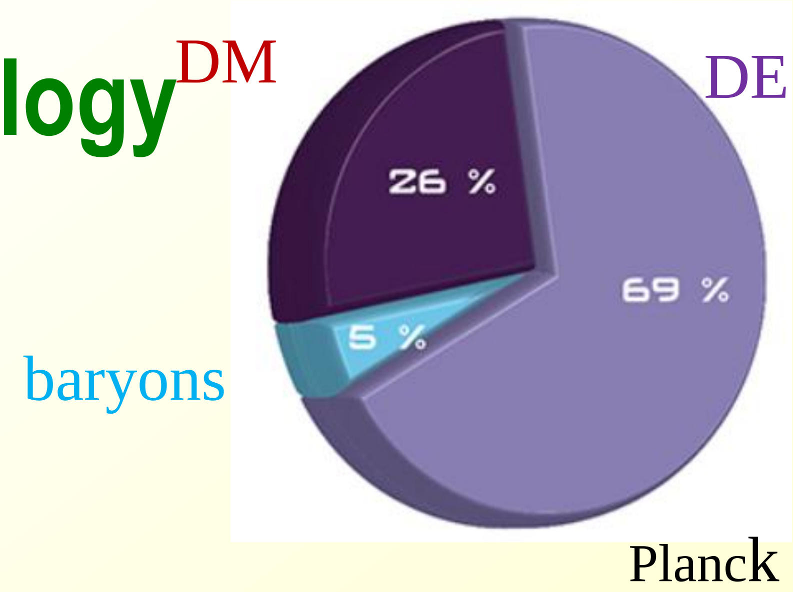
Main questions in cosmology



Matter in the Universe

Dark matter/visible matter vs z

Dark energy:

Is it varying with time?

How is the Universe re-ionized?

End of the dark age: cosmic dawn, EoR

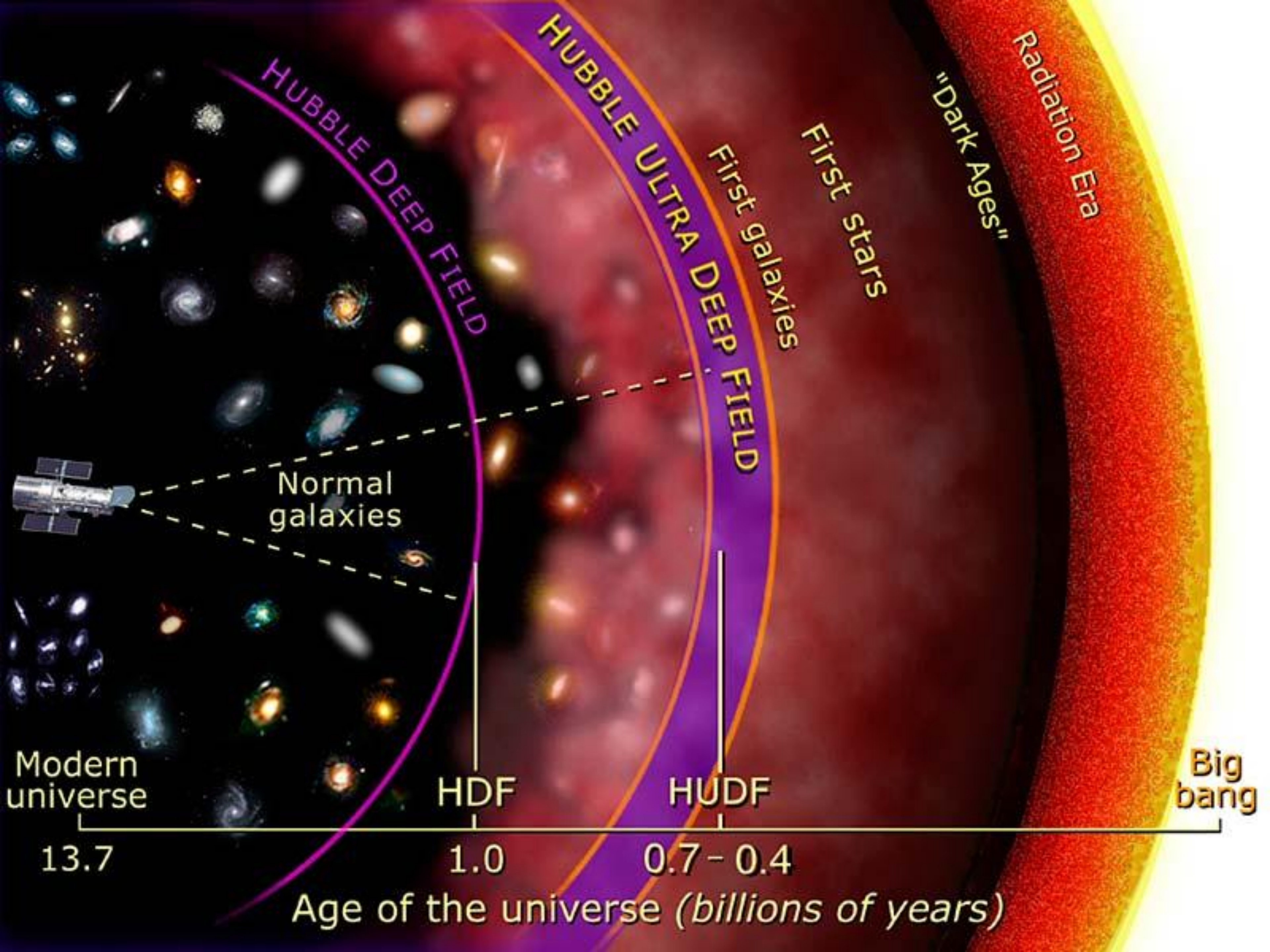
How do baryons assemble into the large-scale structures?

Galaxy formation and evolution (mergers, cold accretion)

Star formation history, quenching

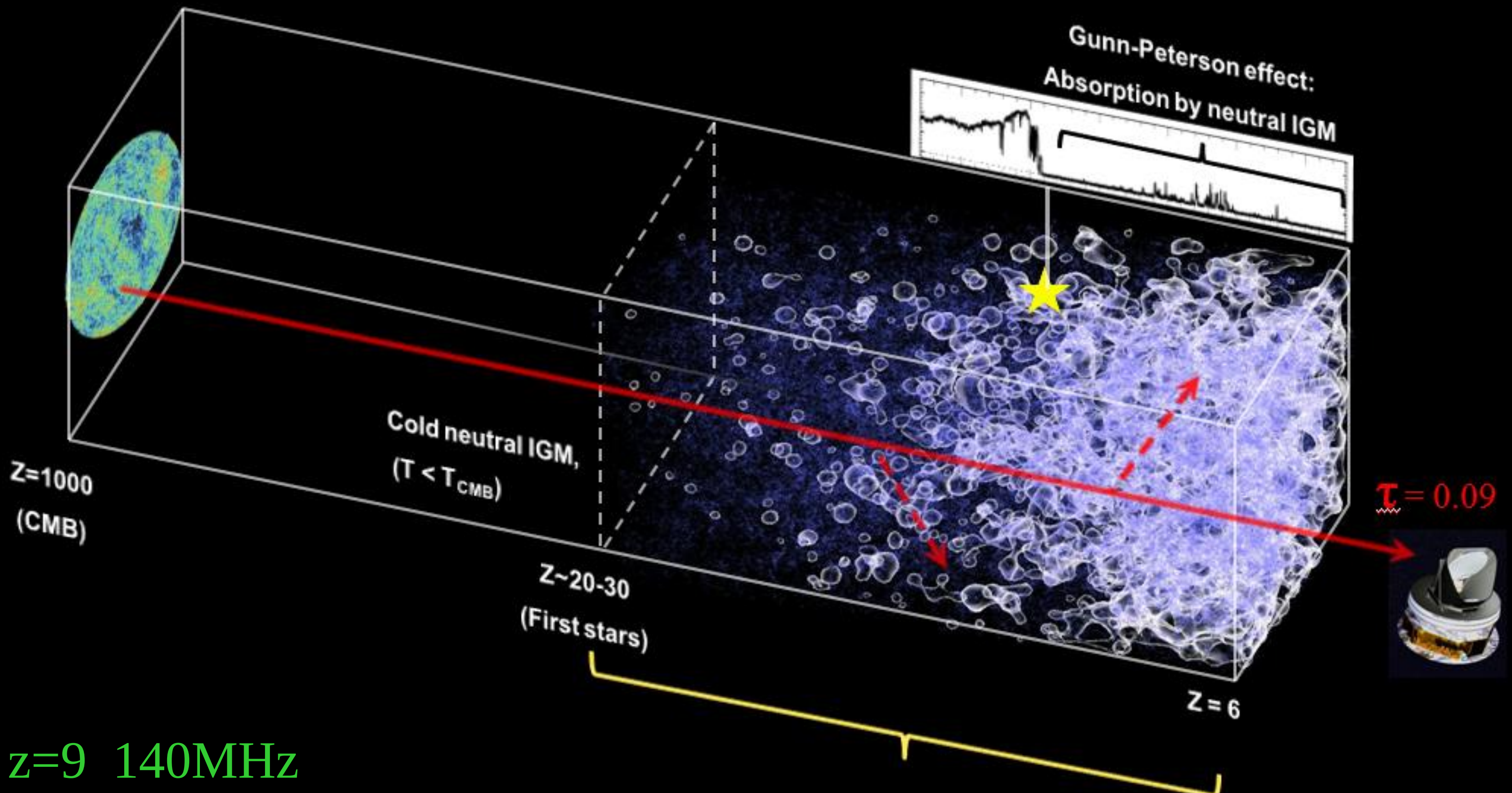
Environment: groups and galaxy clusters

Strong-gravity with pulsars and black holes



HUBBLE DEEP FIELD
HUBBLE ULTRA DEEP FIELD
First galaxies
First stars
"Dark Ages"
Radiation Era
Normal galaxies
Modern universe
HDF
HUDF
Big bang
13.7
1.0
0.7 – 0.4
Age of the universe *(billions of years)*

The epoch of reionization:



z=9 140MHz
Z=12 109 MHz
z=19 70MHz

21 cm tomography =>

- Source nature
- Luminosity fonction
- Cosmological constraints
- …

LOFAR (2013)   SKA (2020)

Translation into Main Parameters

1-What is dark energy: w   P= w ρ

Equation of state and nature of DE, through expansion and growth rates, 5 tools: Weak Lensing, BAO, RSD, Clusters, ISW

2-Gravity beyond Einstein: γ

Testing modified gravity, by measuring growth rate exponent γ

3-The nature of dark matter, m_ν

Testing the CDM theory, and measuring neutrino mass

4- The seeds of cosmic structures

Improve   n= spectral index

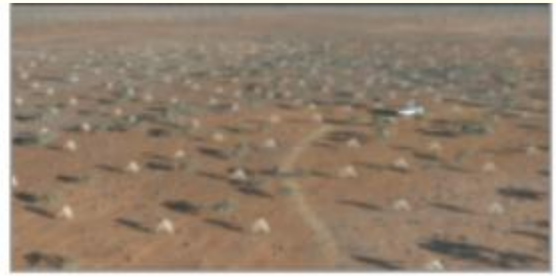
σ_8=amplitude of power spectrum,

f_{NL}= non-gaussianities, inflation?

The SKA phases 1 & 2 < 2015

Africa **Australia**

SKA1
400Me
2017



SKA1_MID
254 Dishes including:
64 x MeerKAT dishes
190 x SKA dishes

SKA1_LOW
50 x Low Frequency Aperture Array Stations

SKA1_SURVEY
96 Dishes including:
36 x ASKAP
60 x SKA dishes

	JVLA/meerKat➔**SKA1-mid**	LOFAR➔**SKA1-low**	ASKAP➔**SKA1-surv**
Sensitivity	6 xJVLA	16xLOFAR	6xASKAP
Survey Speed	74	520	22

SKA2
2022

Africa **Australia**

SKA2_MID
2500 Dishes

SKA2_AA
Mid Frequency Aperture Array Stations

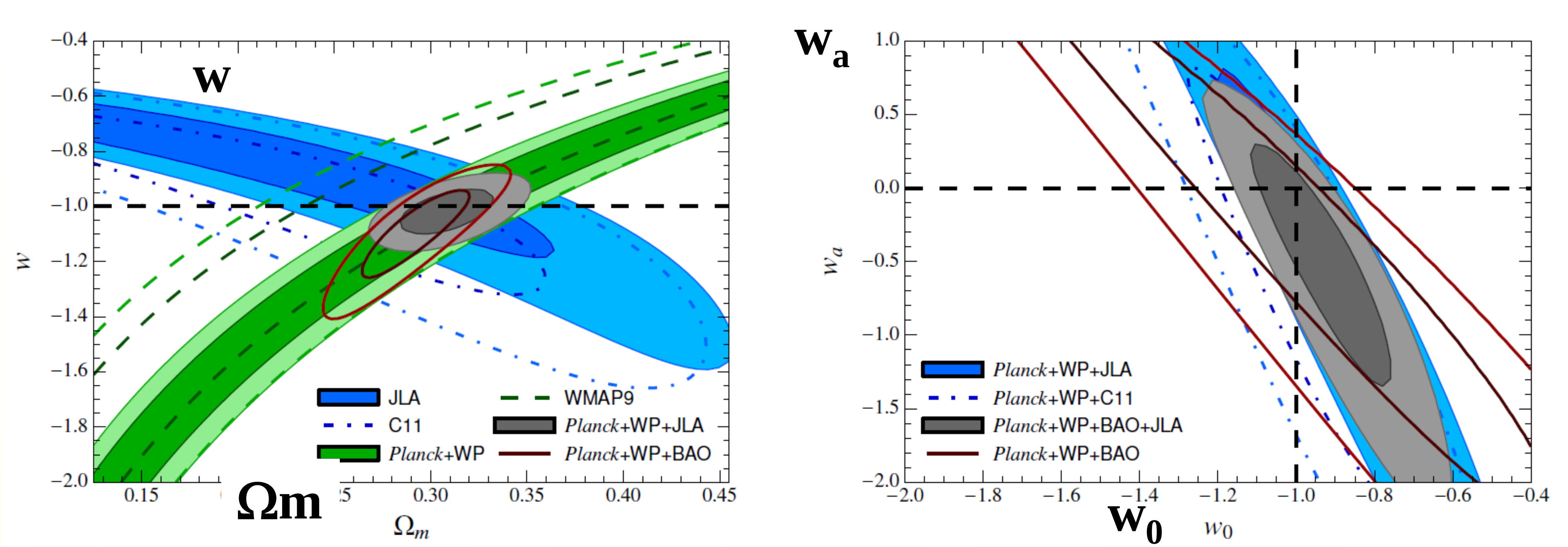
SKA2_LOW
Low Frequency Aperture Array Stations

Accelerating universe from SNIa

2003-2008 SNLS survey, French-Canadian collaboration

SNLS-II (5 yrs) with last calibrations -- **740 SN 0 < z < 1**

$\Omega m = 0.295 \pm 0.034$ $w = -1.018 \pm 0.057$



Betoule et al 2014

Assuming flat universe

$P = w\rho$ $w(a)=w_0 + w_a (1-a)$

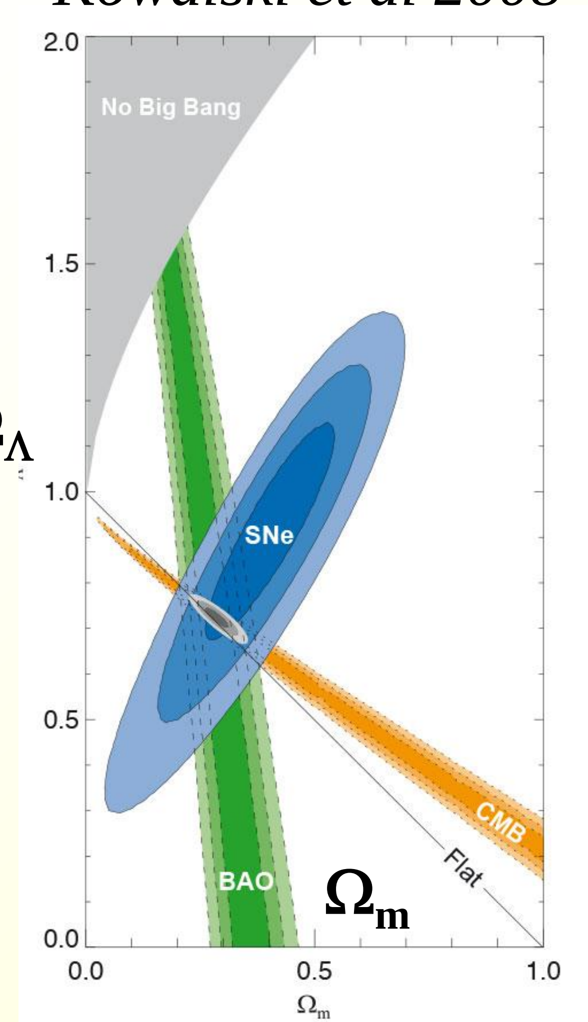
with $a=1/(1+z)$

CMB and Dark energy

Concordance model, between CMB, Supernovae Ia, Large-scale structure (LSS) (weak lensing, BAO= Baryonic Oscillations)

Kowalski et al 2008

Ω_Λ

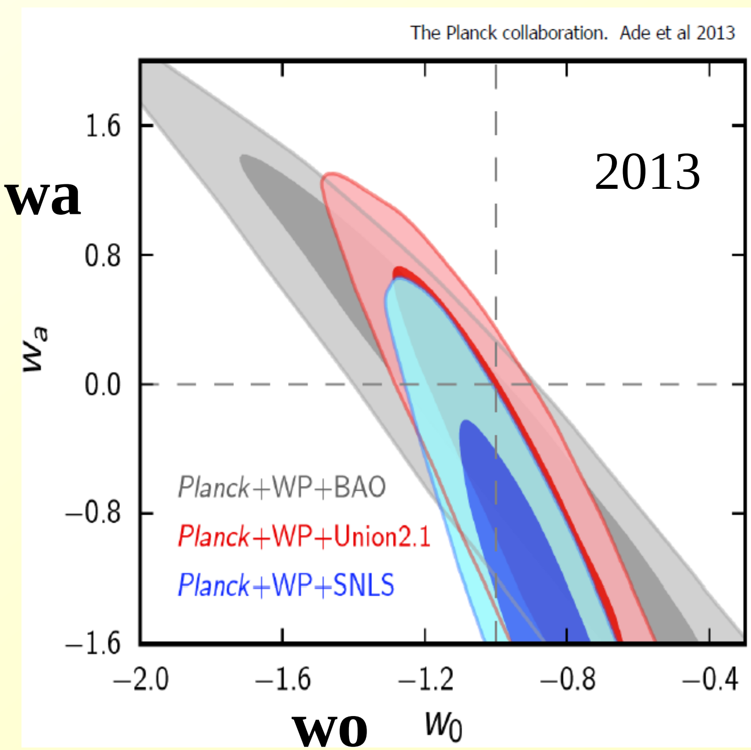


$P = w\,\rho$ $\quad$ $w(a)= w0 + wa\,(1-a)$

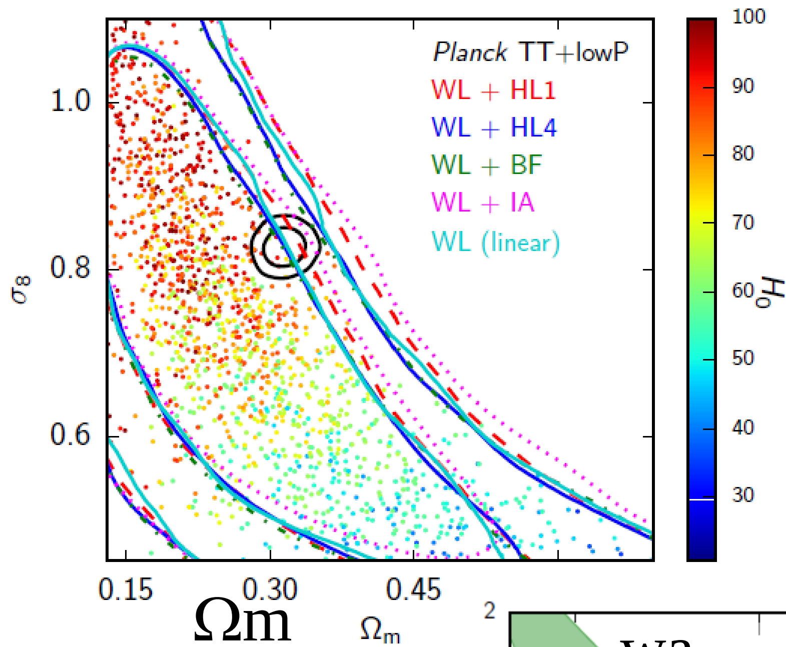
wo~-1

wa~0

wa



Current constraints: Planck + others

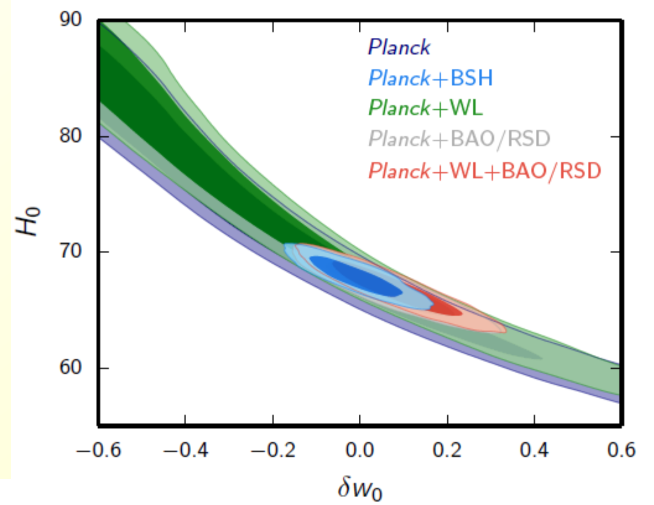


HL: Halo Fit, BF:AGN feedback

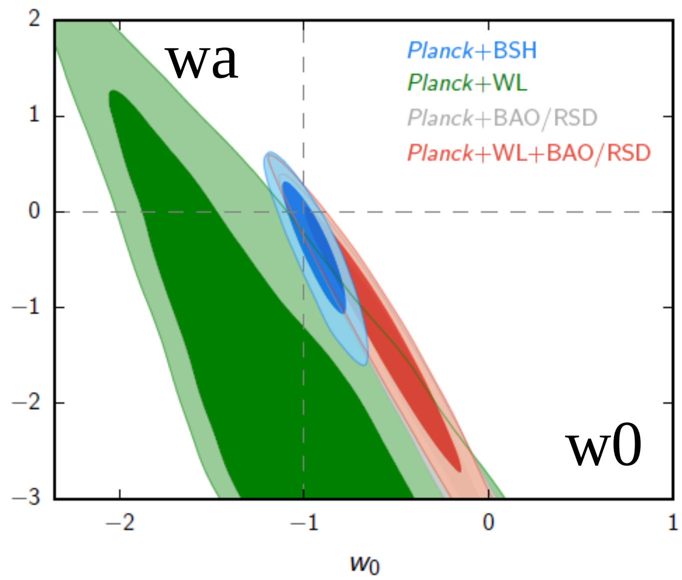
IA :intrinsic alignment

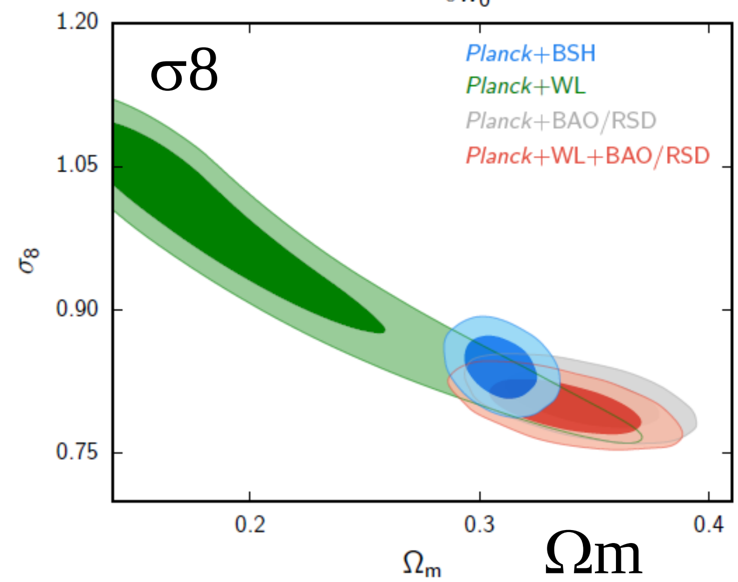
BSH:

BAO+SNIa+H_0



Planck 2015





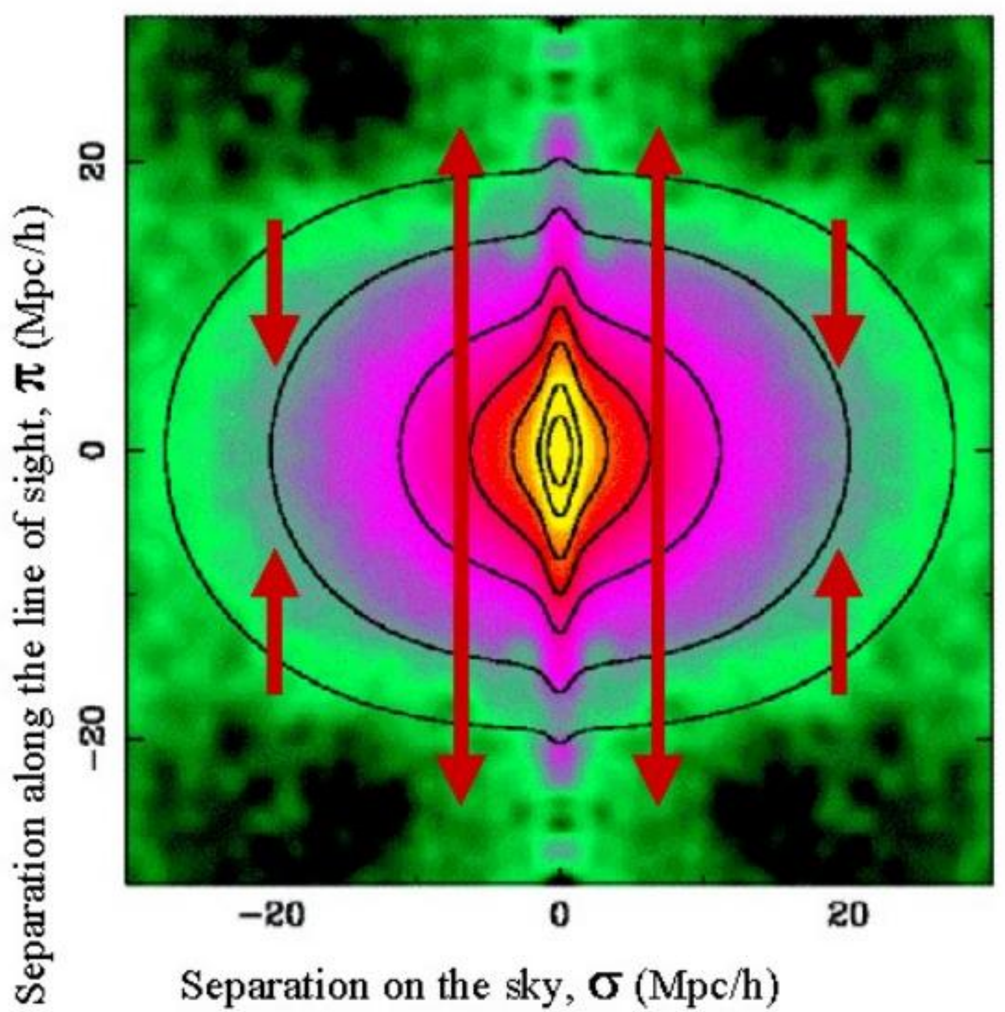
RSD Redshift space distortions

Distortions due to peculiar velocities on the line of sight (fingers of god!)

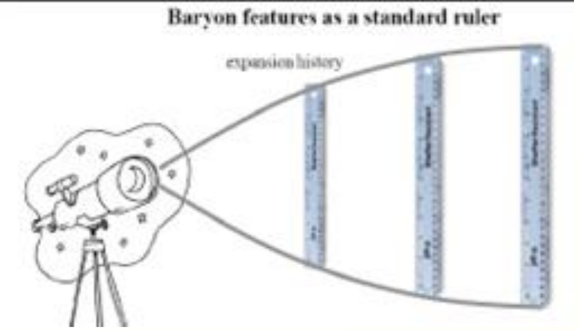
Kaiser effect in clusters
Systematic infall

More than random allows to determine

$\beta = \Omega_m^{0.6}/b$
bias $\delta_{galaxies} = b\ (\delta_{mass})$
and σ_{gal}



The 2dF Galaxy Redshift Survey Team (2001)

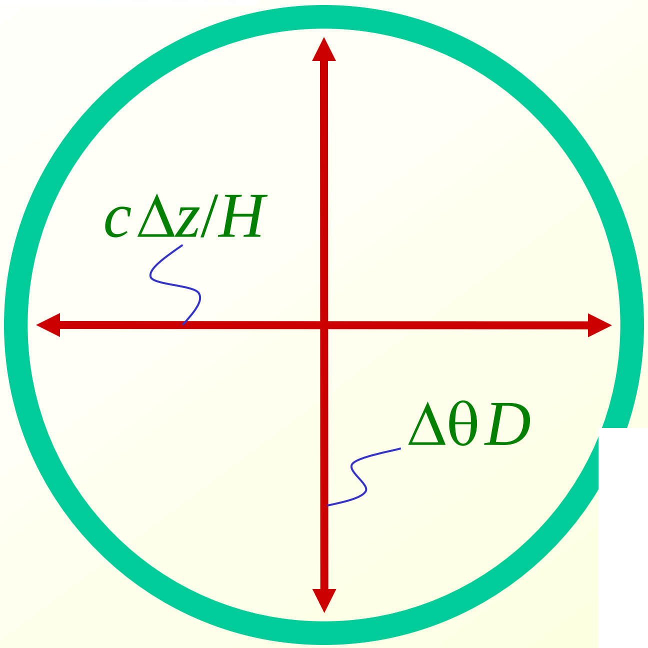


BAO: Standard Ruler

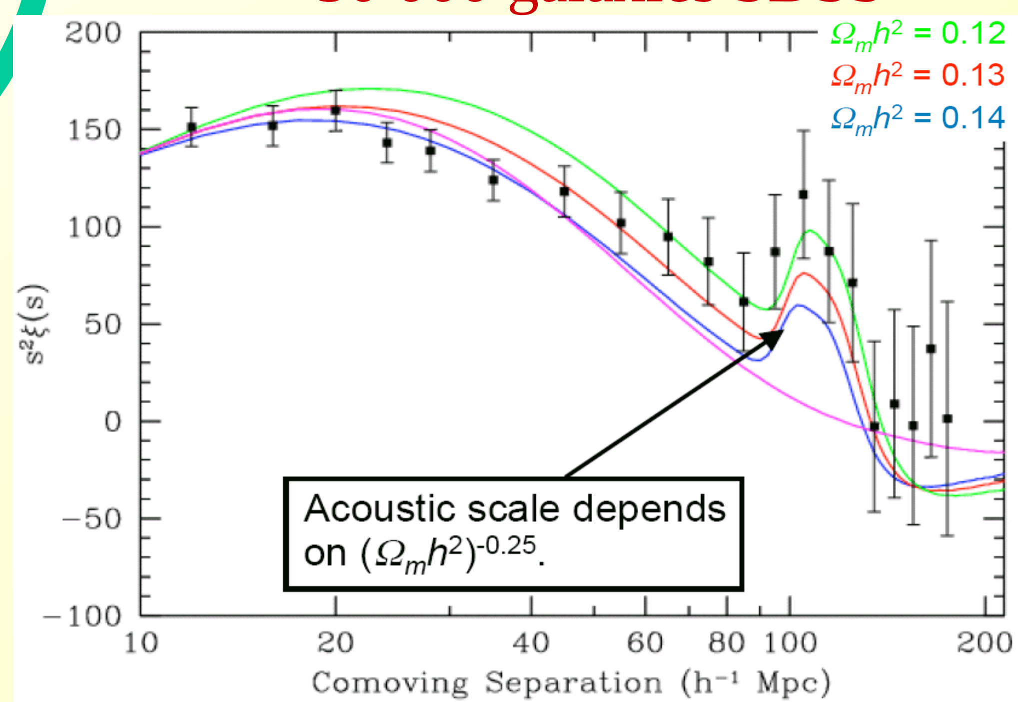
Alcock & Paczynski (1979)
Test of cosmological cst

Could test the bias b
Or $\beta = \Omega_m^{0.6}/b$

Observer



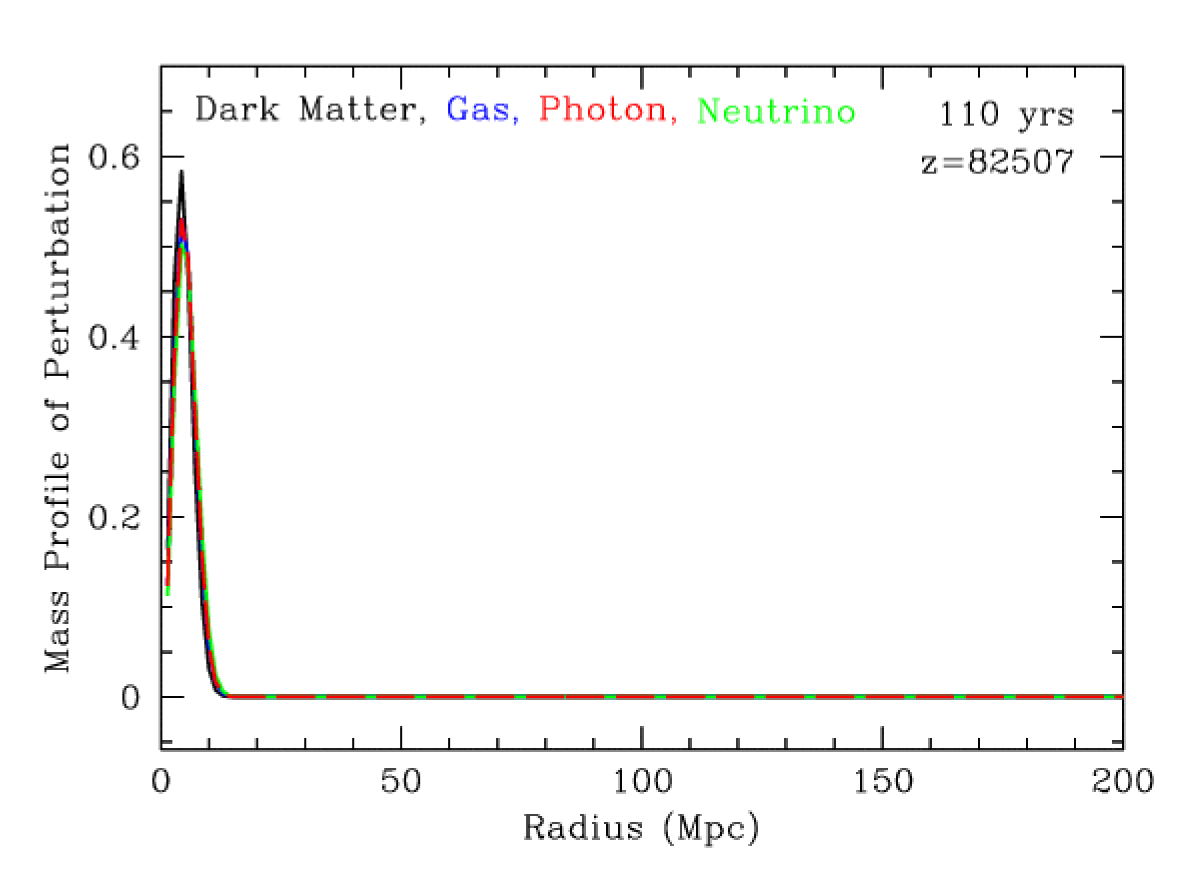
Eisenstein et al. (2005)
50 000 galaxies SDSS



$$c\Delta z/H = \Delta\theta D$$

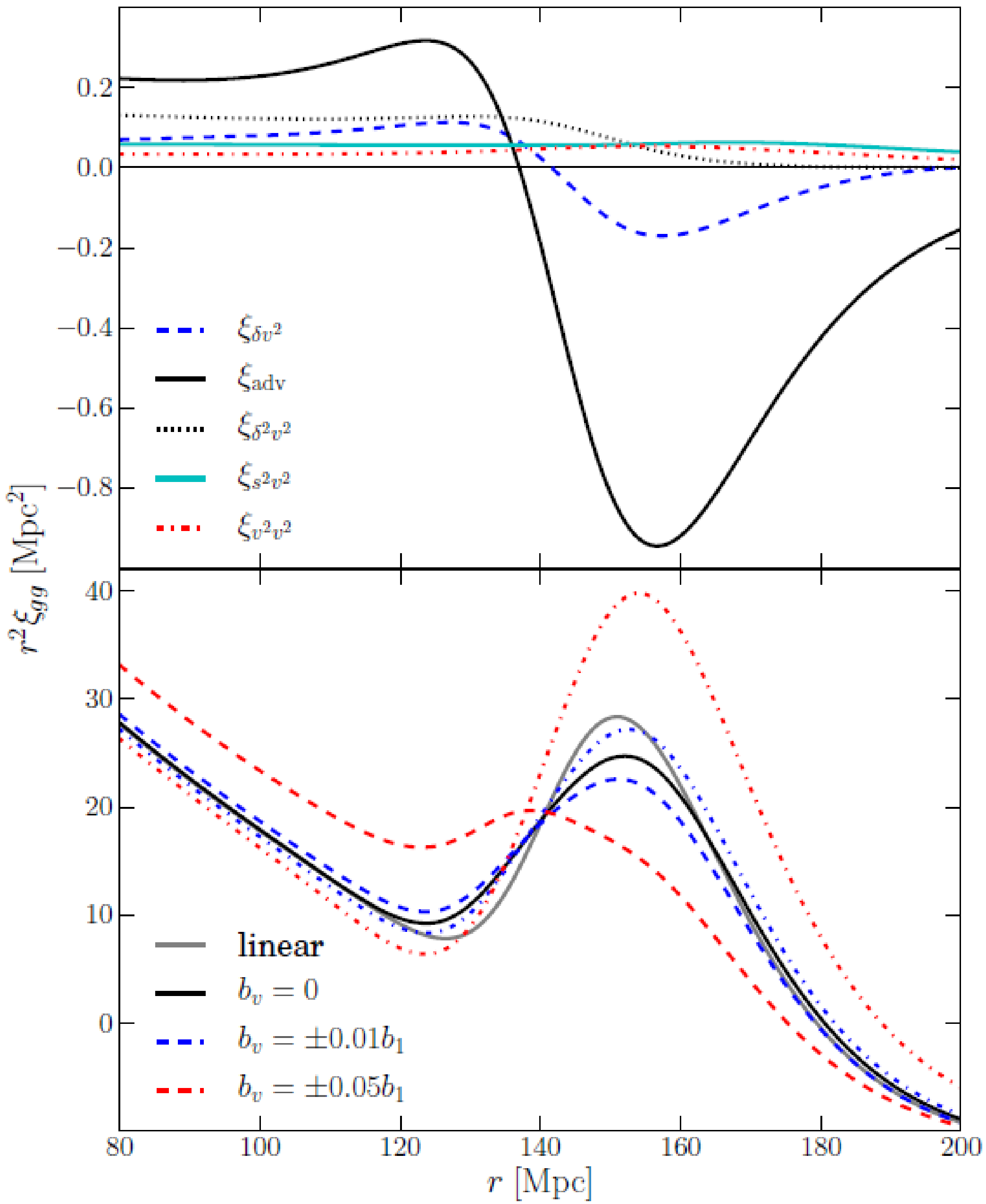
➔Possibility to determine H(z)

Animated version: BAO



From Eisenstein, & CMBFAST

Peculiar velocity DM-baryons



It was realized in 2010 that V_b-V_{DM}= 33km/s at decoupling

The HI σv = 6km/s

➔Supersonic

➔Could impact small mass structures

Blazek et al 2015

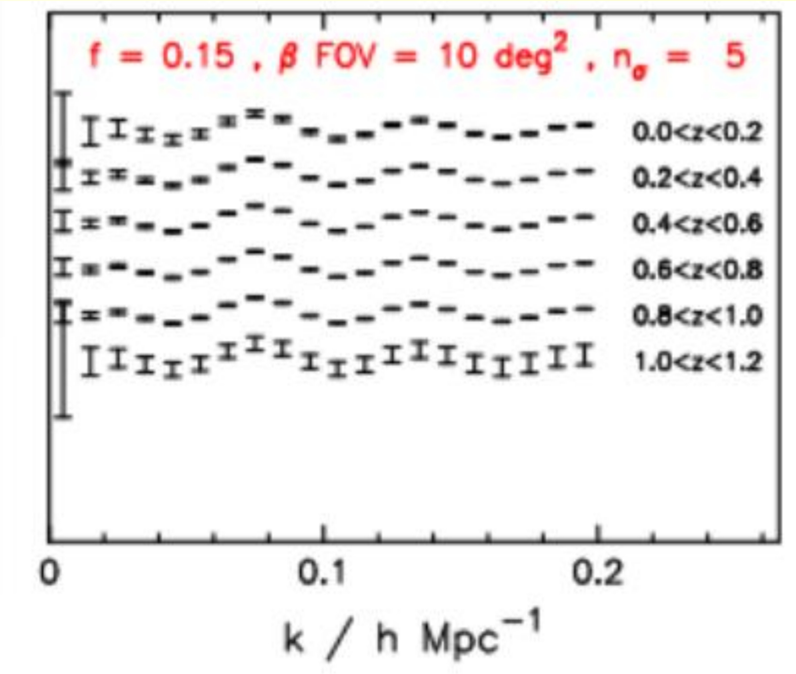
HI surveys for BAO with SKA-1

All sky survey: 4 10^6 gal z=0.2 3π sr
Wide-field survey 2 10^6 gal z=0.6 5000 deg^2
Deep-field survey 4 10^5 gal z=0.8 50 deg^2

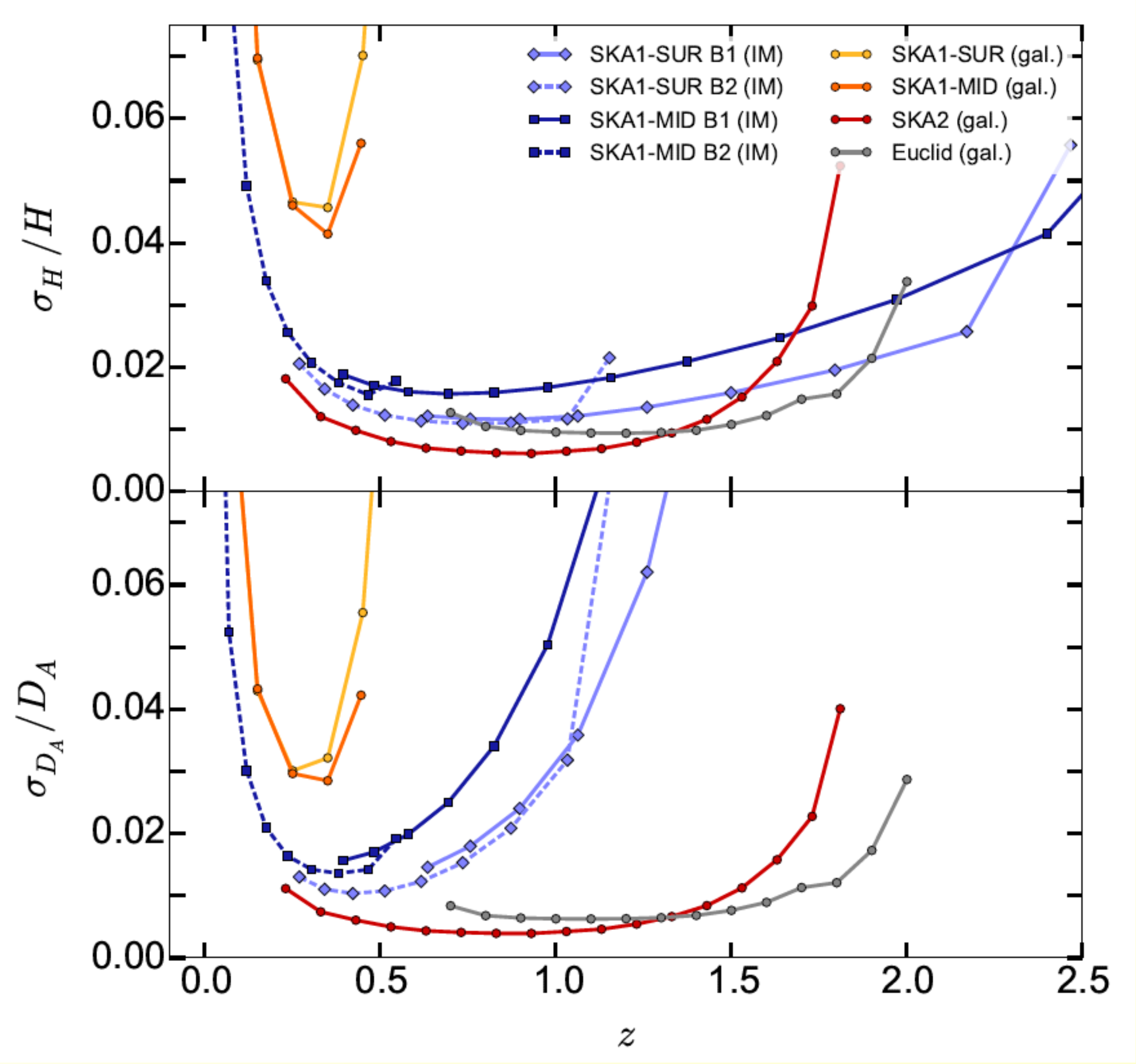
More competitive: HI intensity mapping 30 000 deg^2 up to z=3
Deep and wide, large volumes, ~Euclid

SKA2 will help to provide pure sample
1 billion HI galaxies in total

Weak shear
10 billions galaxies in continuum



Radial and transverse BAO

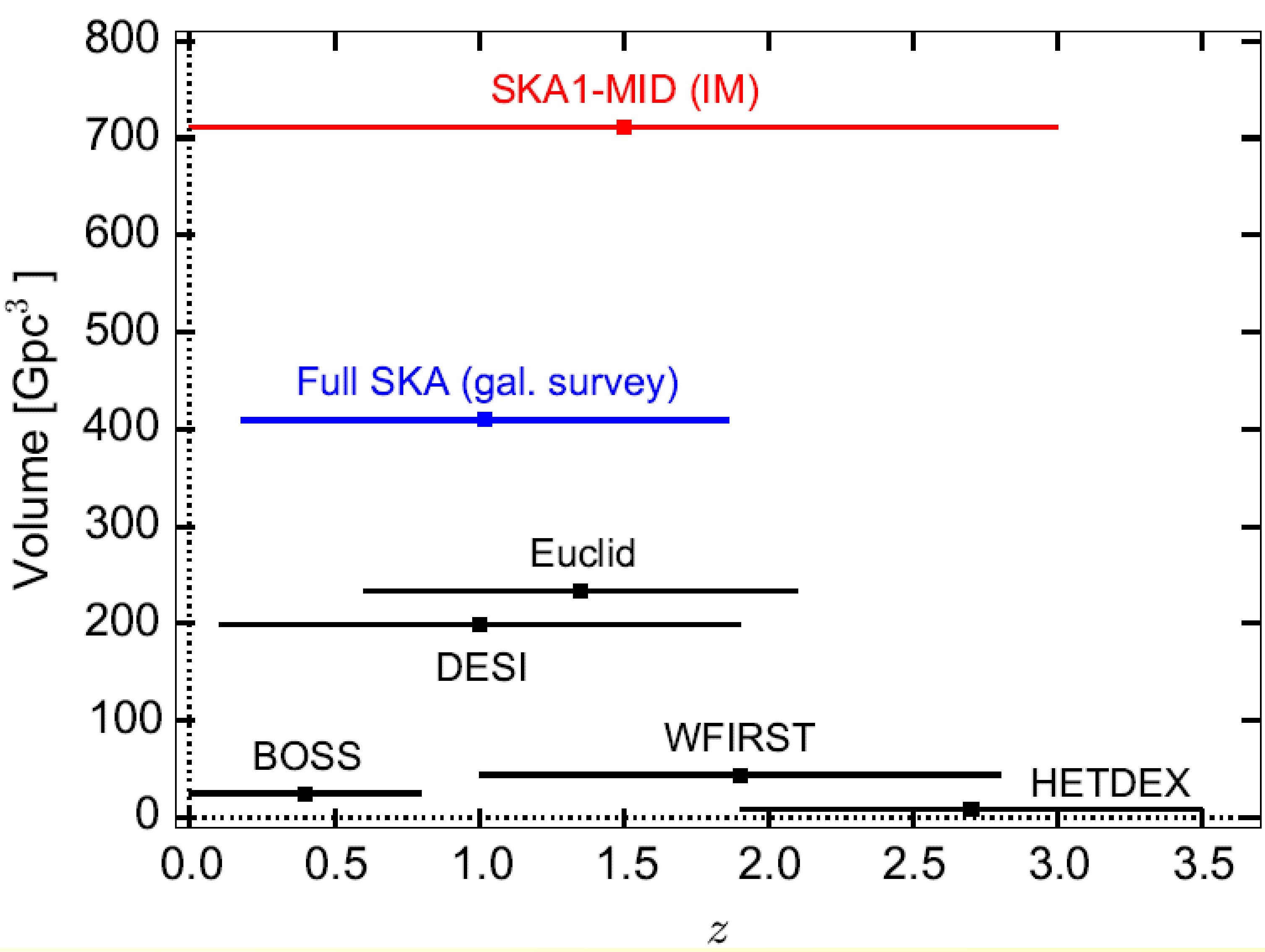


IM: HI Intensity mapping
Gal: HI galaxy surveys

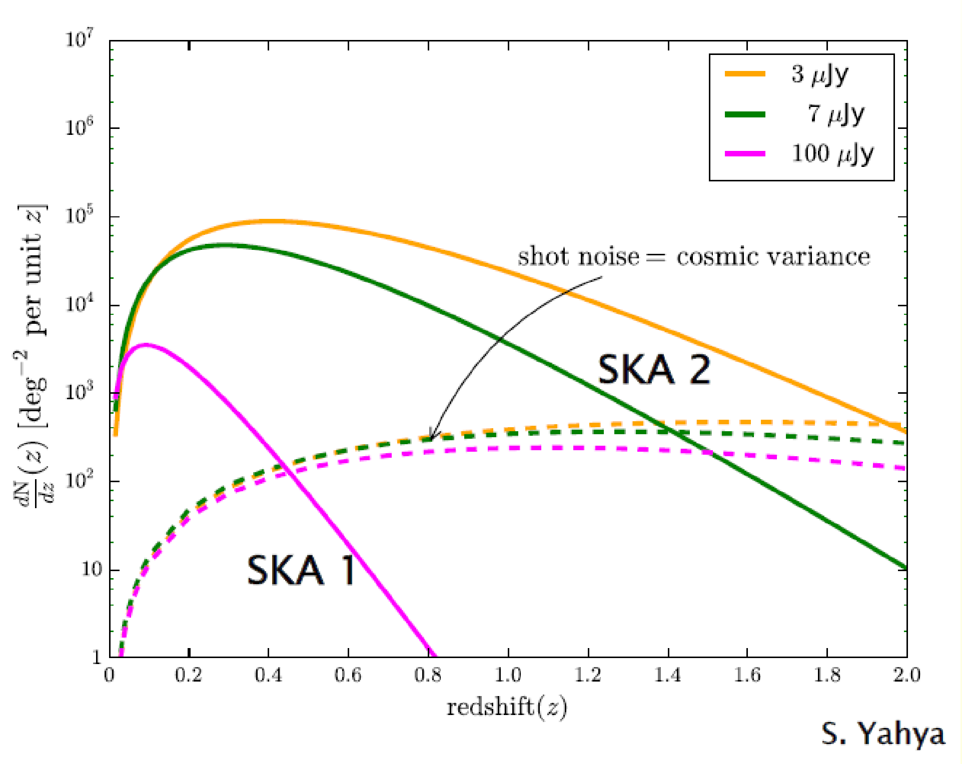
B1 low-frequency band
B2 high-frequency band

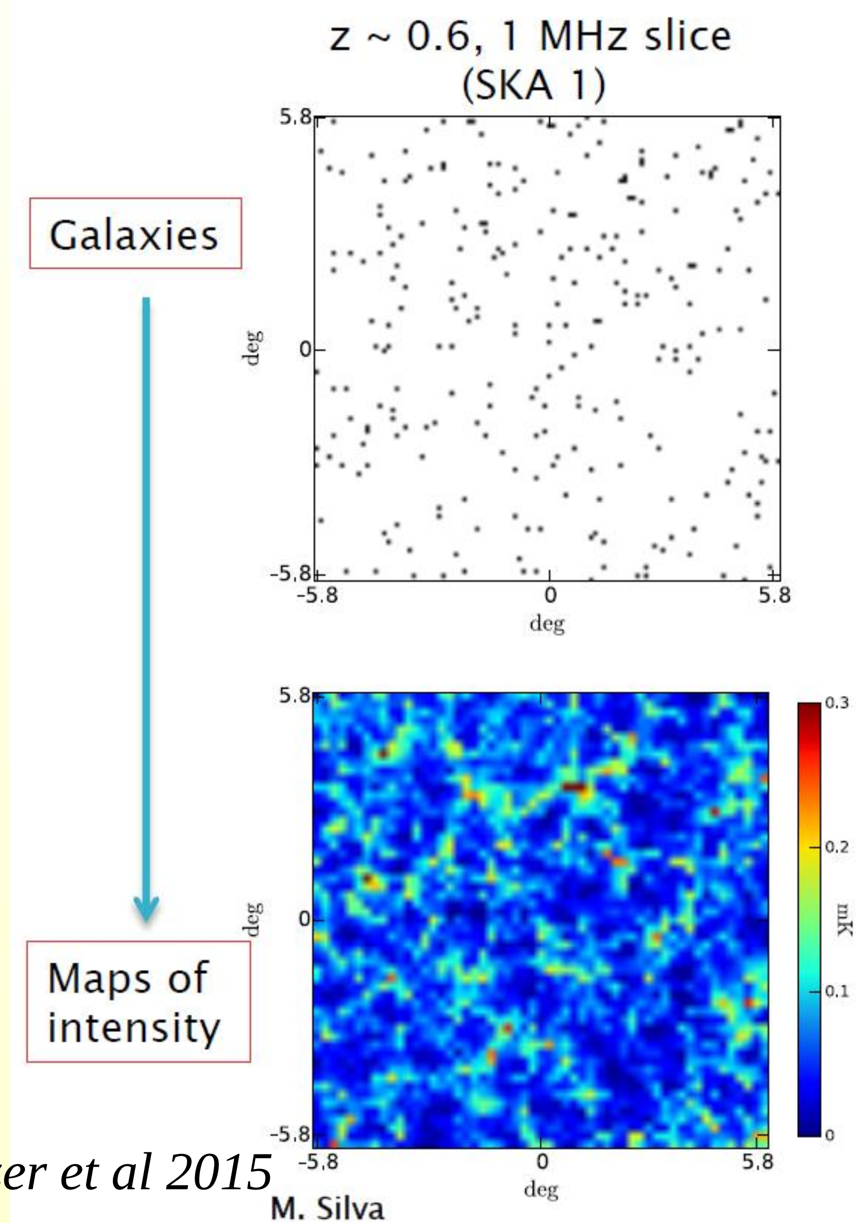
Maartens et al 2015

Comparison of Volume covered



HI gal survey vs intensity mapping





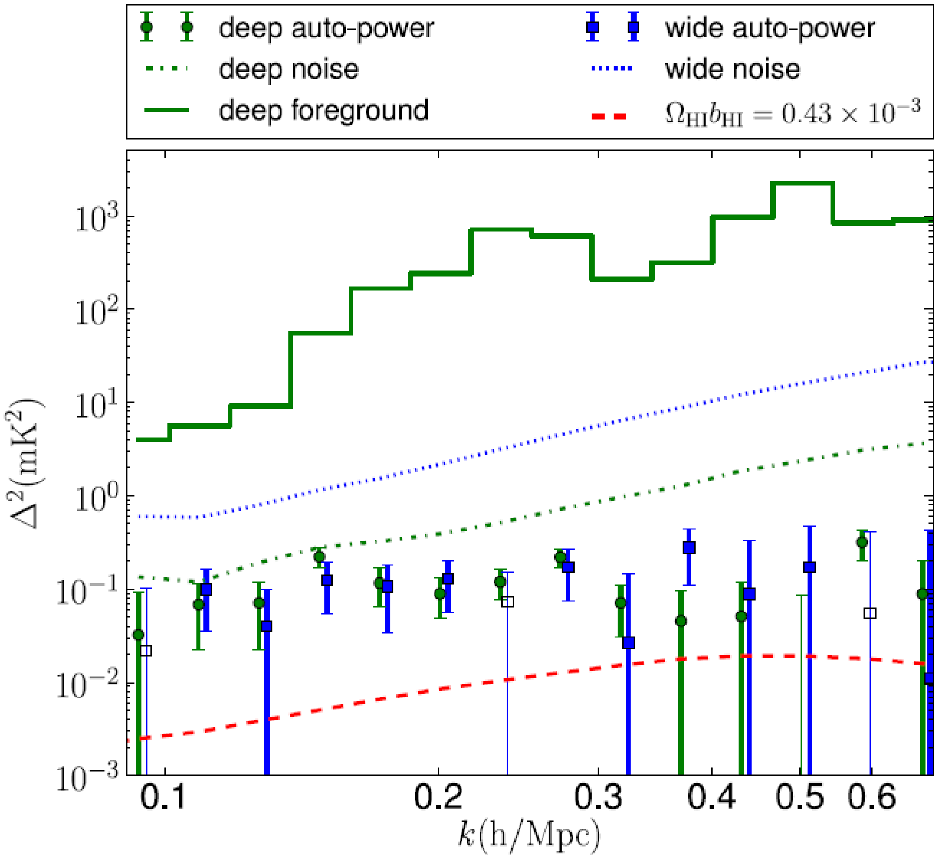
HI intensity mapping: main problem is the foreground, due to continuum

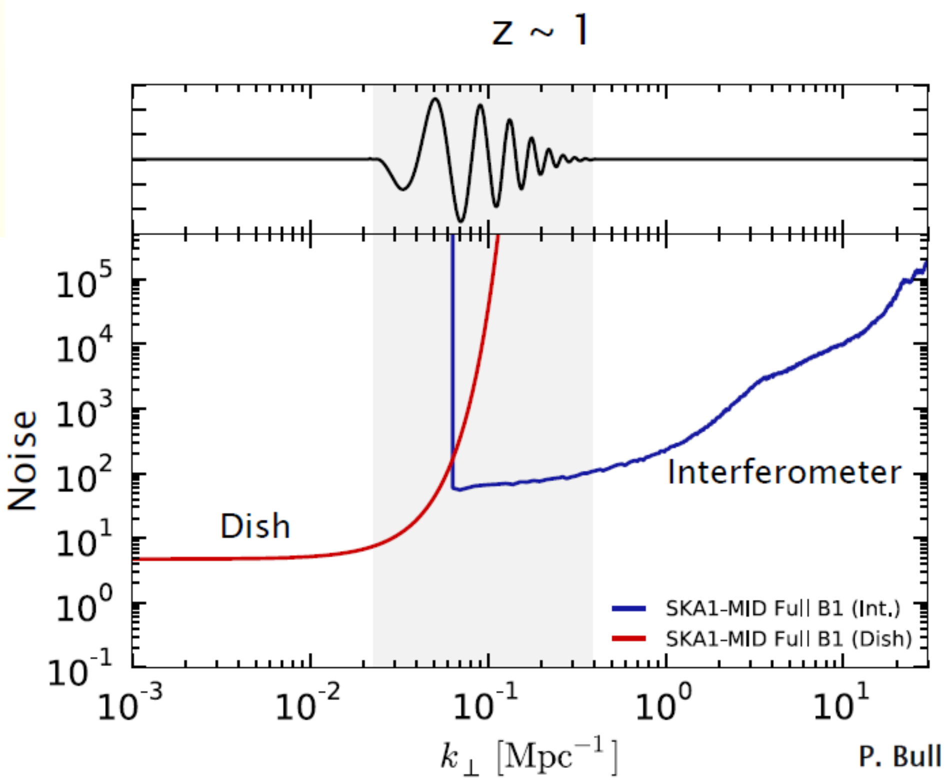
1000 x the expected signal

Not smoother in frequency, but fewer bright spectral degrees of freedom *Switzer et al 2015*

First results HI intensity mapping (GBT)

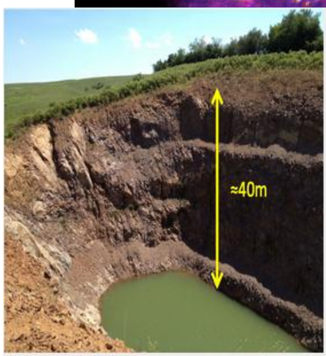
Not enough short baselines
(BAO require 20m)
➔use N single dishes
(auto-correlation)



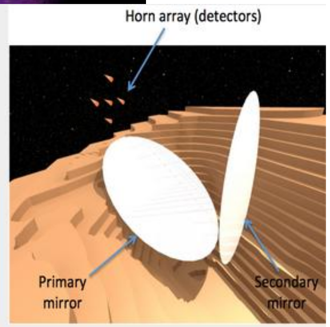


Switzer et al 2014

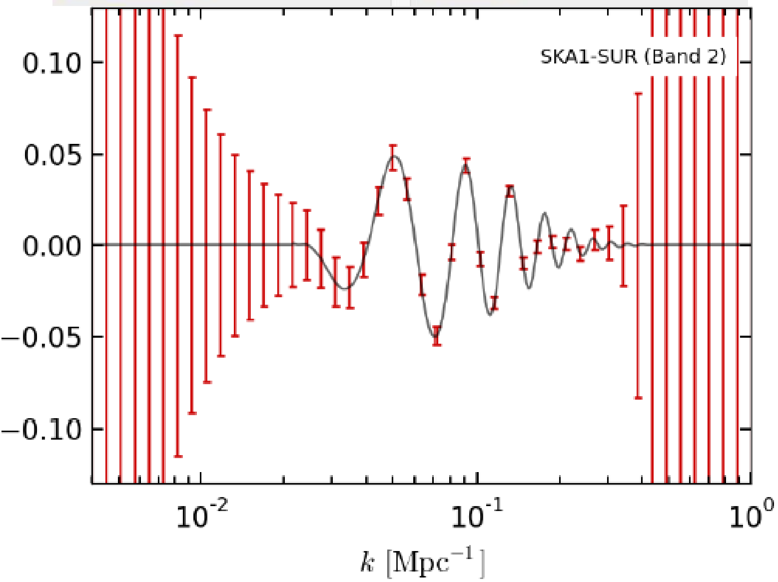
BAO with SKA1 Intensity mapping

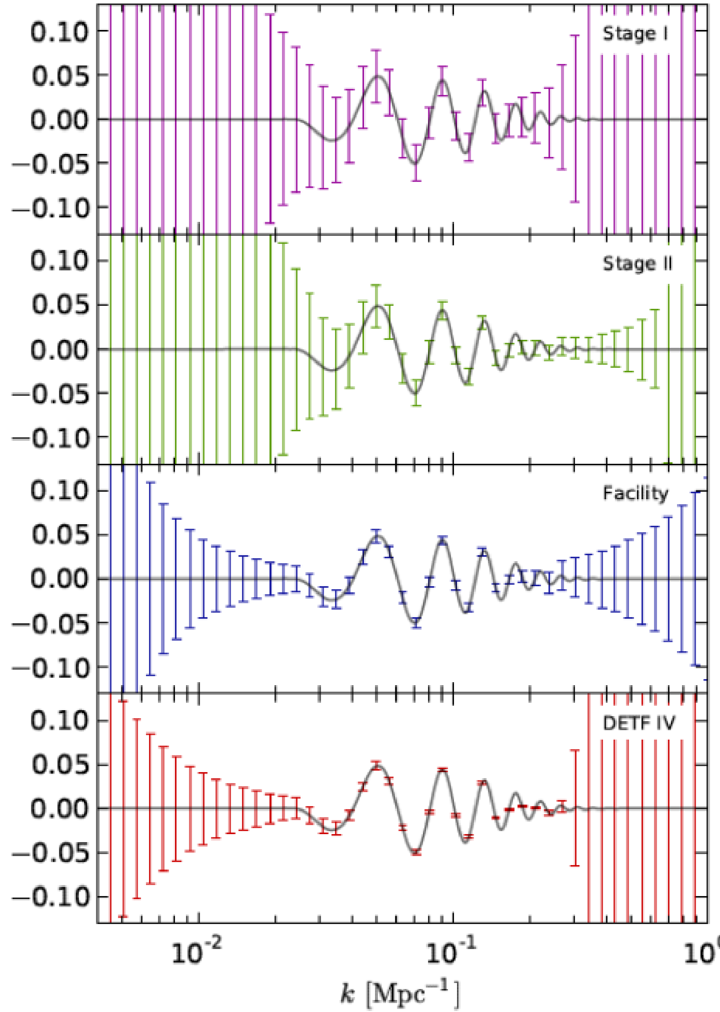


Quarry Castrillon



A 3D view of the BINGO telescope





40m

~ BINGO

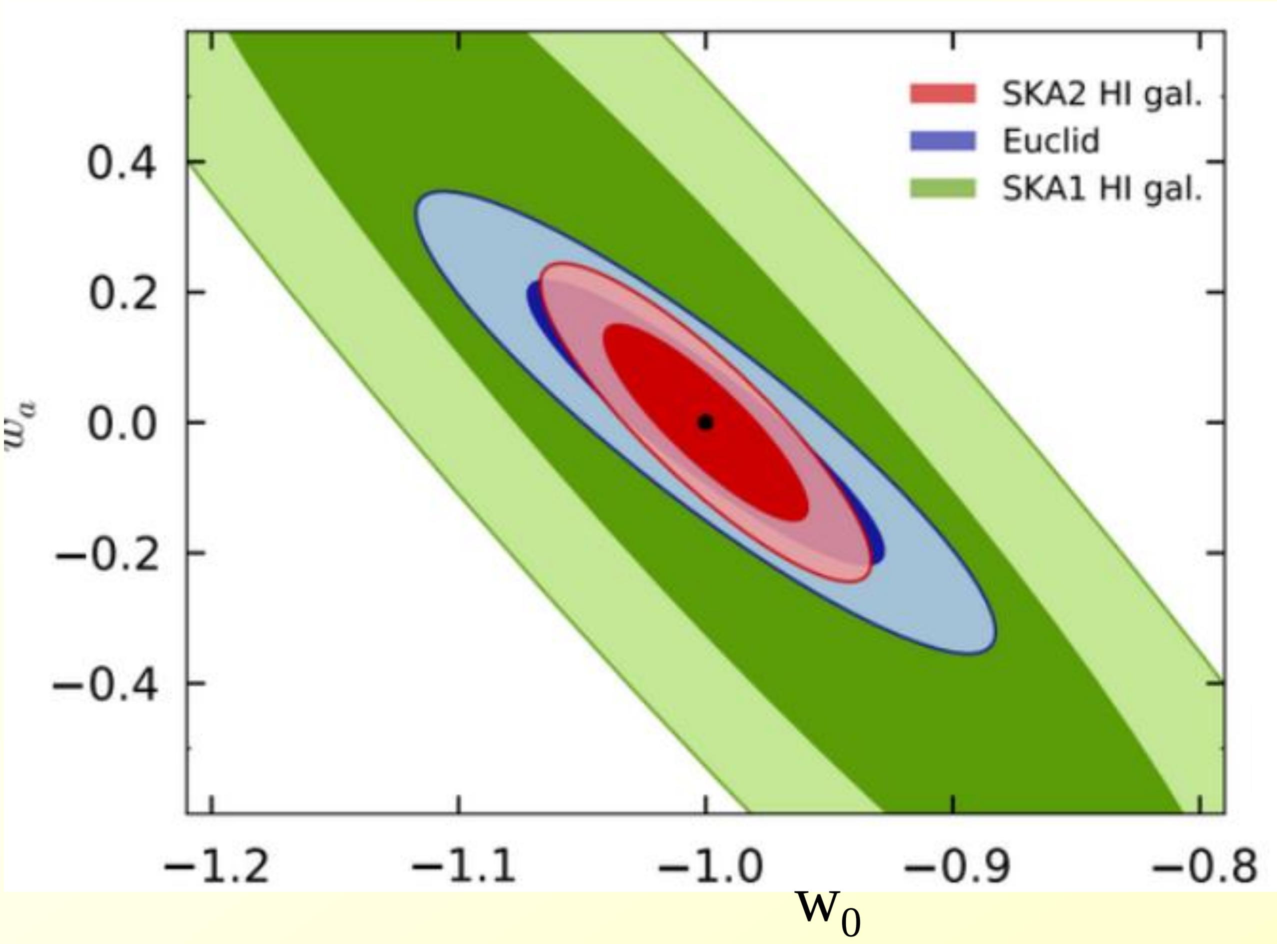
z=0.13-0.48

~ MeerKAT

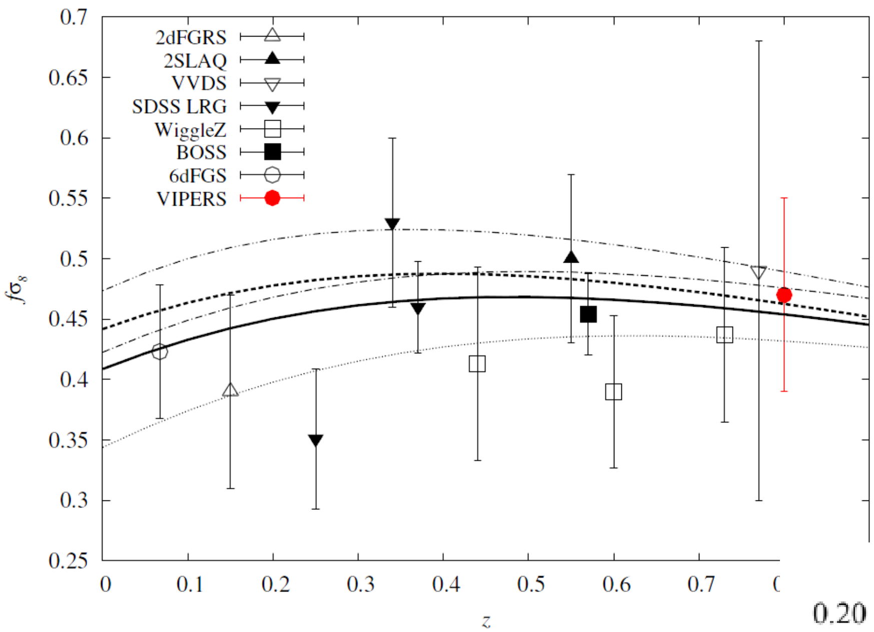
~ SKA1-Mid base (up to z ~ 2.0)

~ Euclid

Constraints on DE with HI gal survey



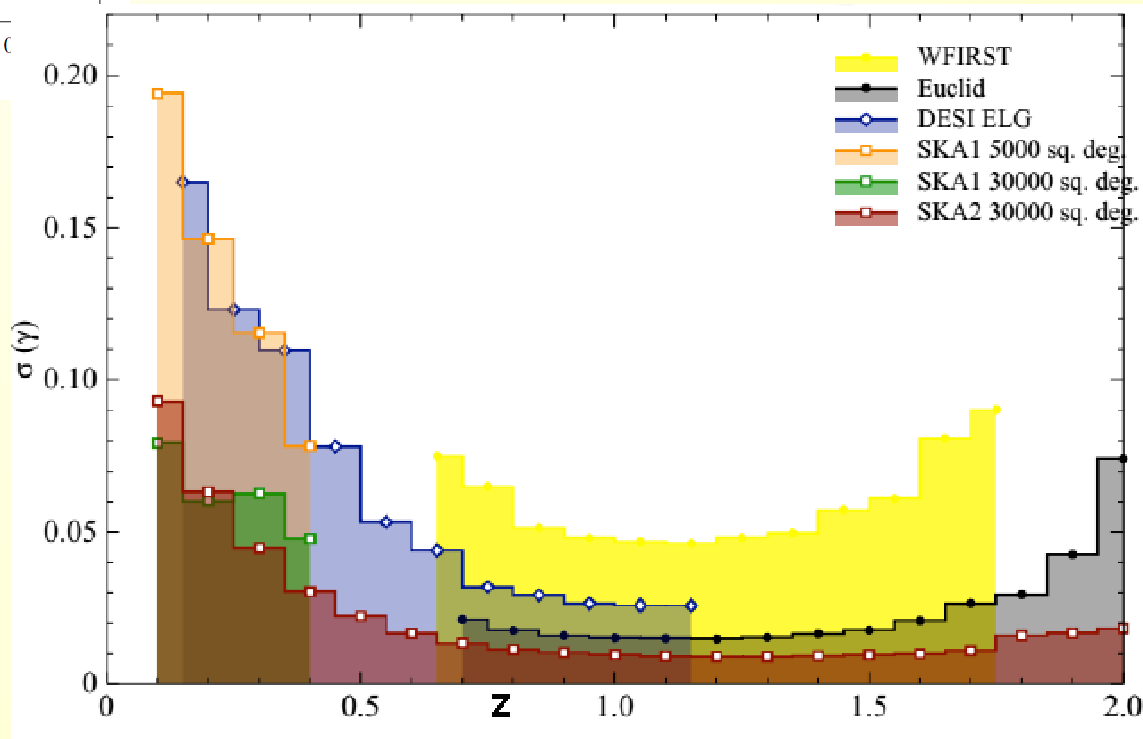
RSD: Redshift Space Distortions



Various galaxy surveys
VIPERS, de la Torre et al 2013

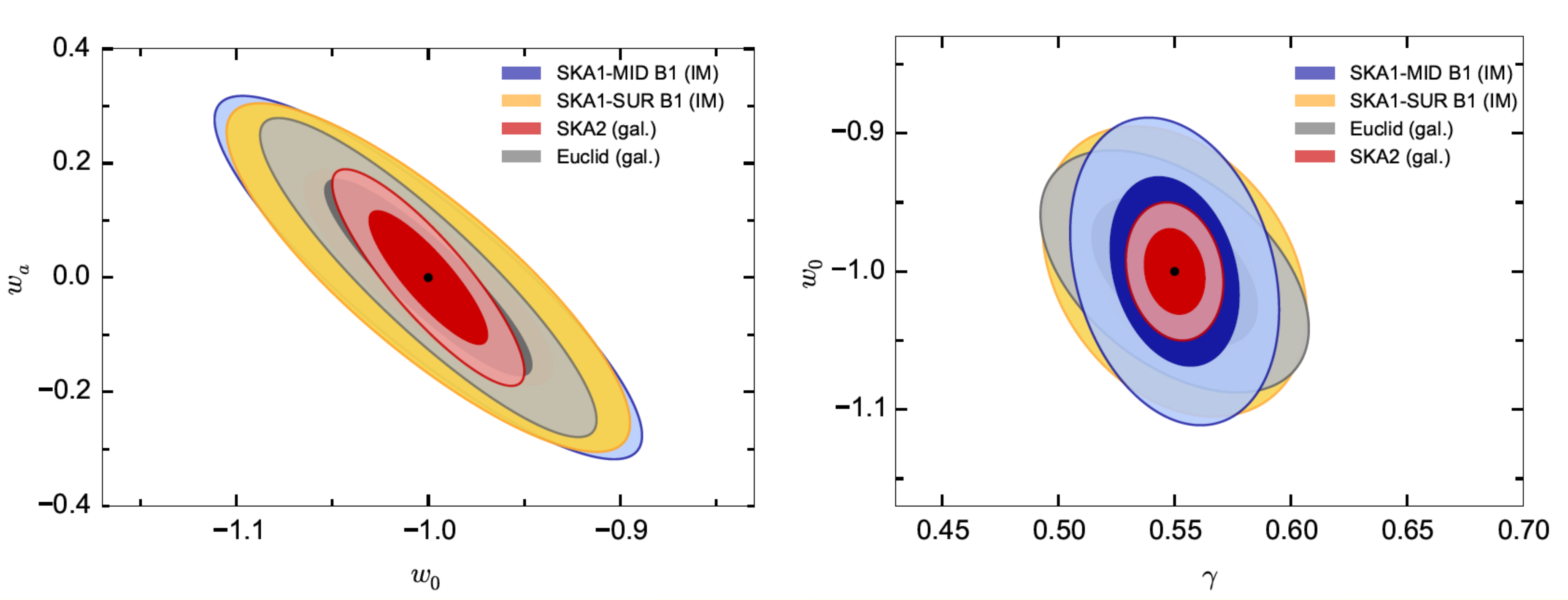
Thick line: GR gravity

Dahed or dotted lines
Modified gravity
DGP (Dvali et al 2010
f(R) models, etc..



RSD constraints on DE and γ

Raccanelli et al. 2015



Dark energy

Modified gravity

Continuum surveys with SKA1

In 2yrs achieve 2 μJy rms would provide ≈4 galaxies arcmin^{2} (>10σ)

PSF is excellent quality circular Gaussian from about 0.6 – 100”
With almost uniform sky coverage of 3π sr

➔Total of **0.5 billion radio sources, for All sky survey**
for weak lensing and Integrated Sachs Wolfe (WL, ISW)

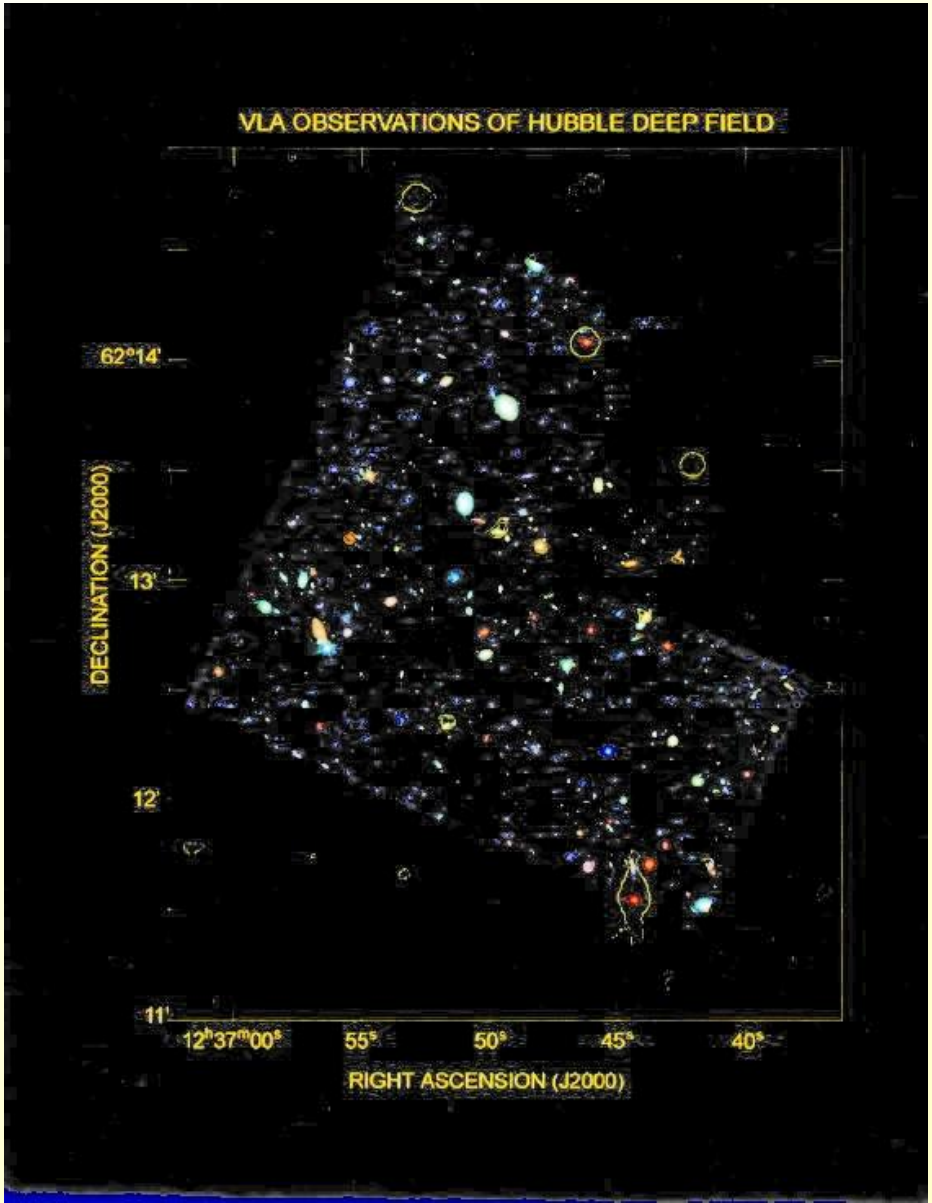
For wide-field (5000 deg2) **2 μJy rms** ≈6 galaxies arcmin^{2} (>10σ)
For deep-field (50deg2) **0.1 μJy rms**, ≈20 galaxies arcmin^{2} (>10σ)

Present status of radio surveys

HDF-N 5 x 5 arcmin area to I ~29th magnitude

Fomalont et al., ApJ 475, L5 (1997)

6 sources detected by VLA with $S_{8.4}$ > 12 μJy (50 hour observation)



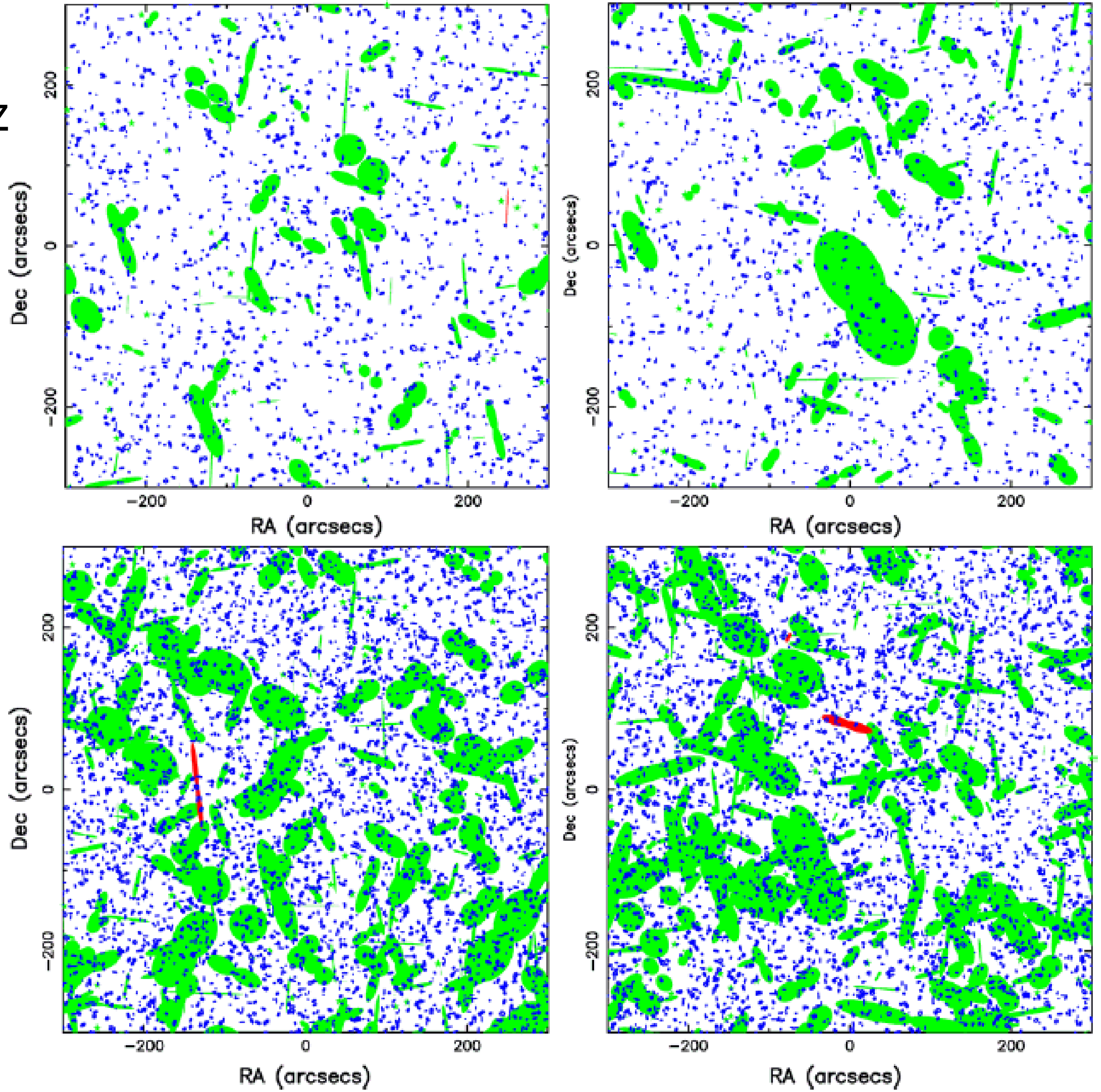
Deep radio sky
10' size, @ 1.4GHz

1mJy top
100nJy bottom
Left and Right
Cosmic variance

FRI: green, double
FRII: red, double

Beamed FRI:
green dot
Beamed FRII:
red dot
Star-forming: disk

Jackson 2004

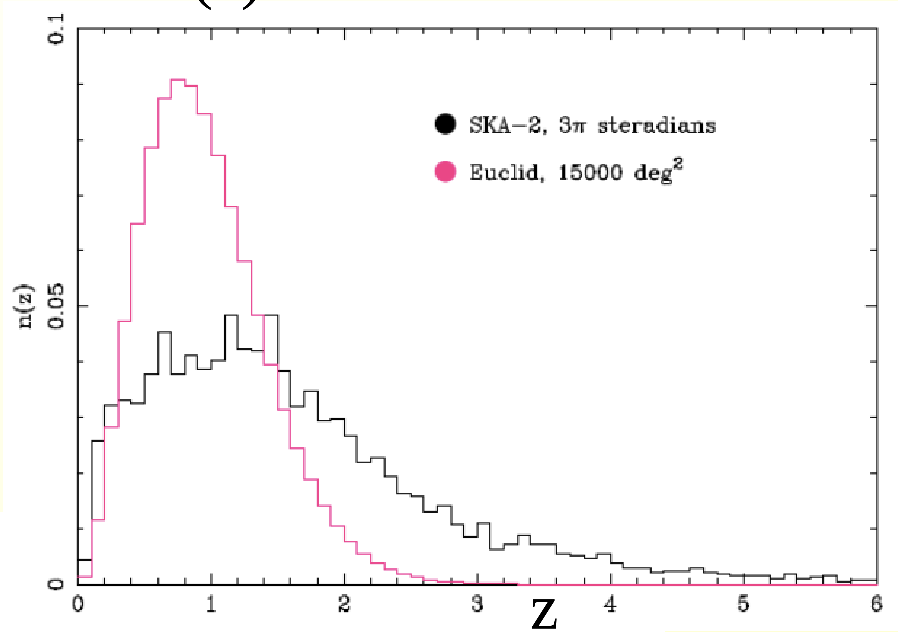


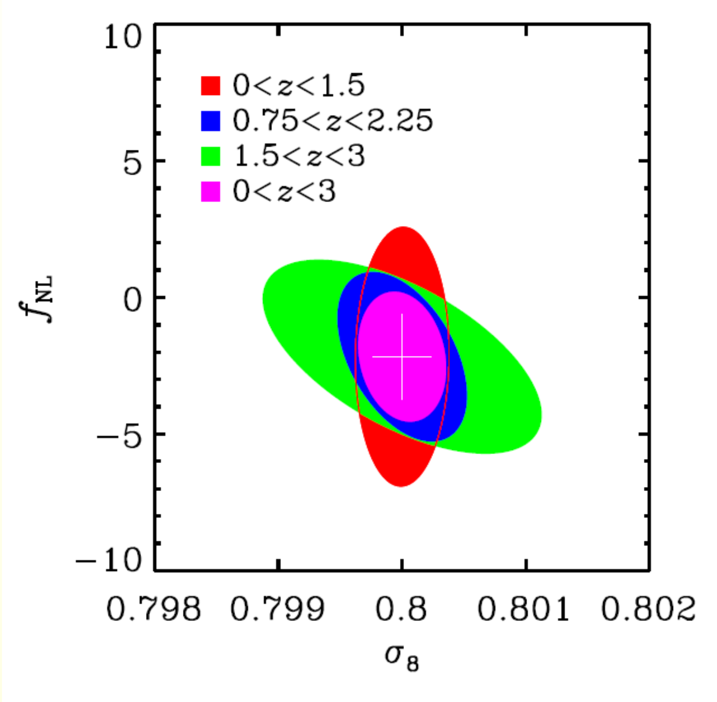
Weak Lensing & LSS in radio

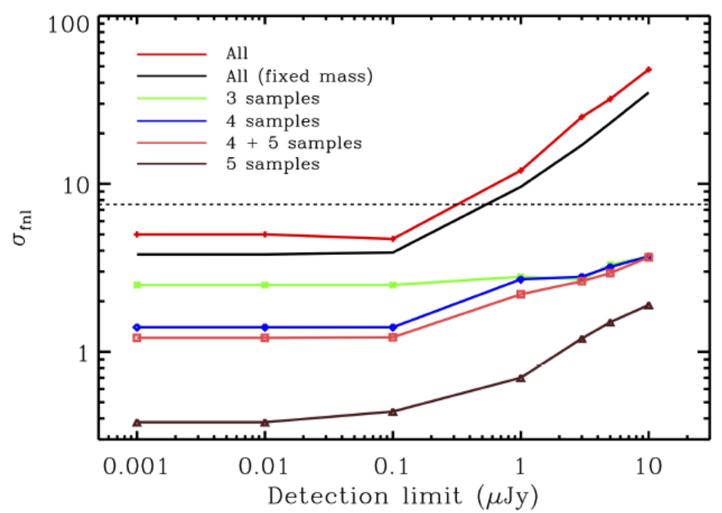
Number of objects
extends to higher z with SKA

The amplitude of non-gaussianity
f_{NL} = -2.2 in standard GR
σ(f_{NL}) = 7.5 (Planck)
= 2.3 (SKA1) & =1 (SKA2)

dN(z) dz

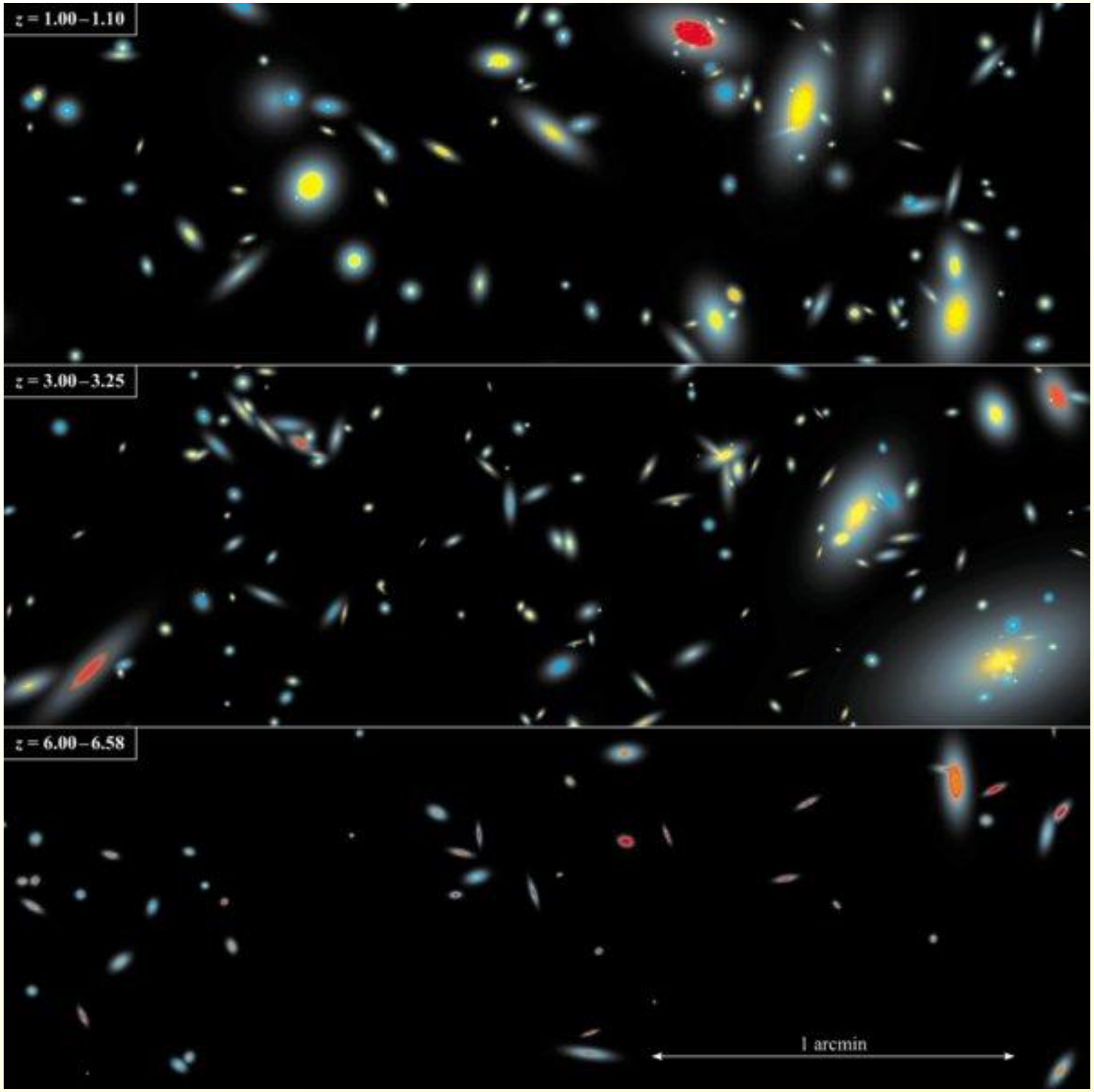






SKA1 &
SKA2
Radio
$\sigma(f_{NL})$

Simulated sky, z=1, 3, 6



Obreschkow et al 09

z=3 scale x10
z=6 scale x100

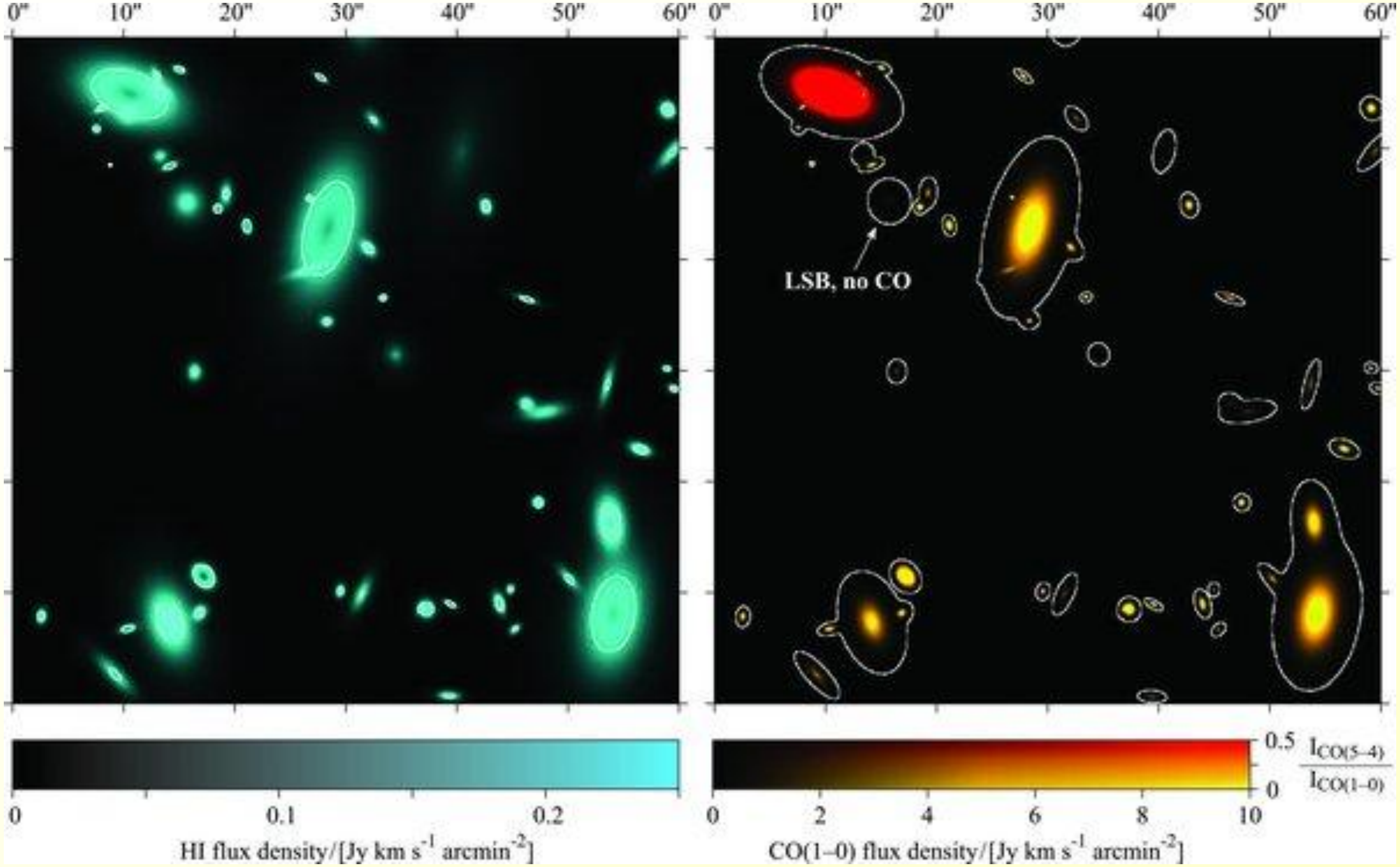
240 Mpc comoving depth
3 x 1 arcmin surface

HI line, and CO lines

Simulating the extragalactic sky

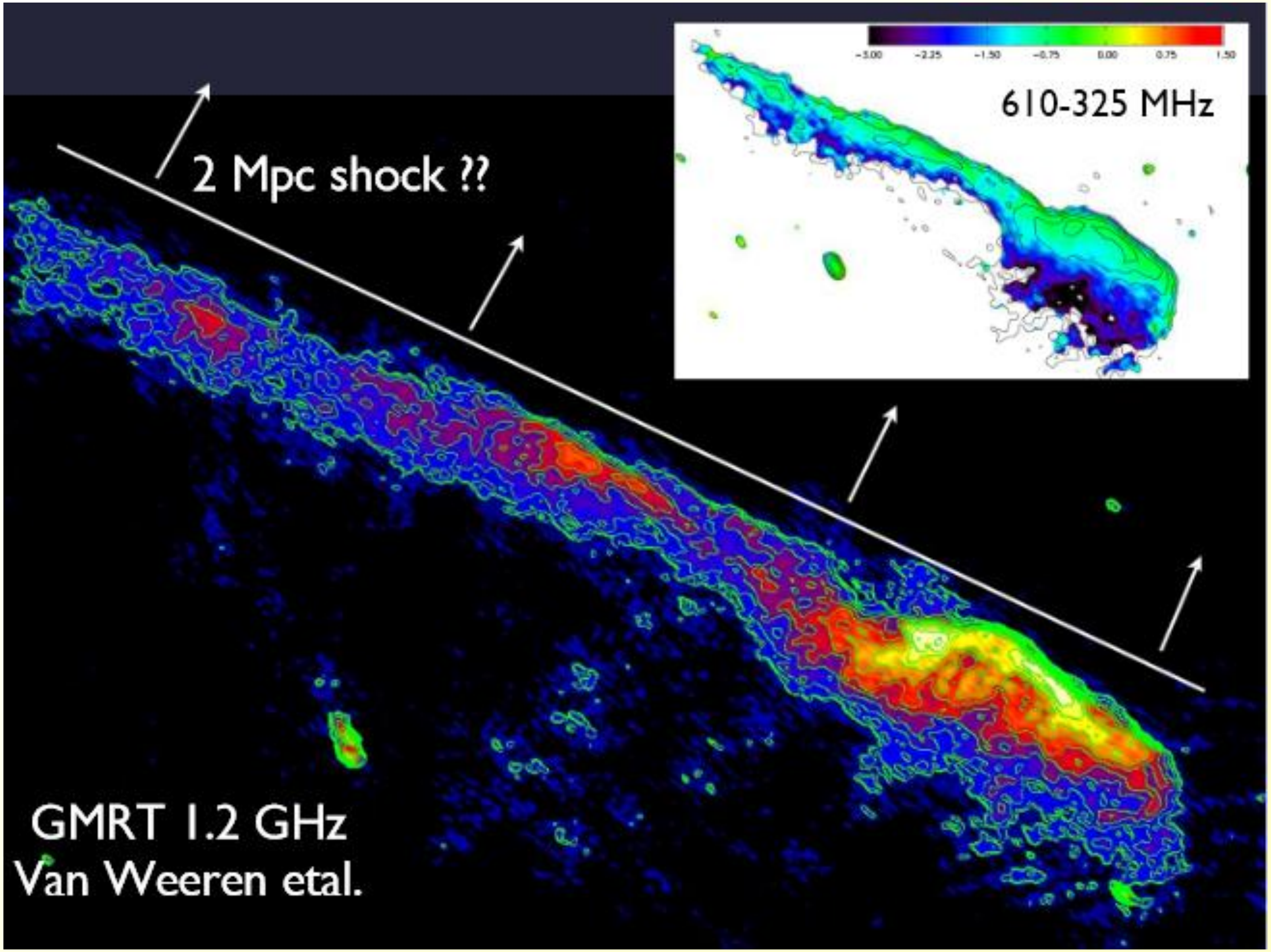
Field of 1 arcmin, z~1

In HI line (SKA) **in CO lines (ALMA**

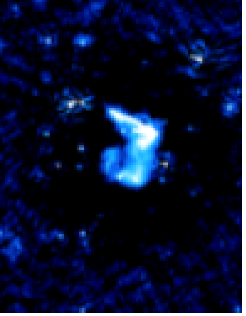


Obreschkow et al 09

Shocks during cluster mergers

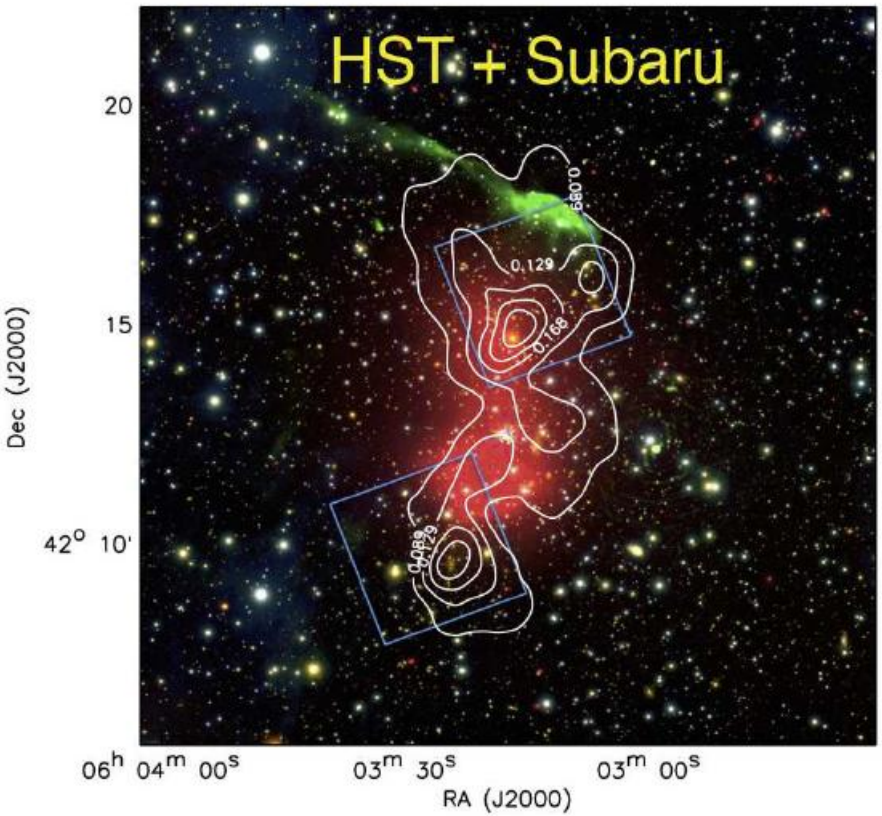


How to produce such a linear shock during a merger?

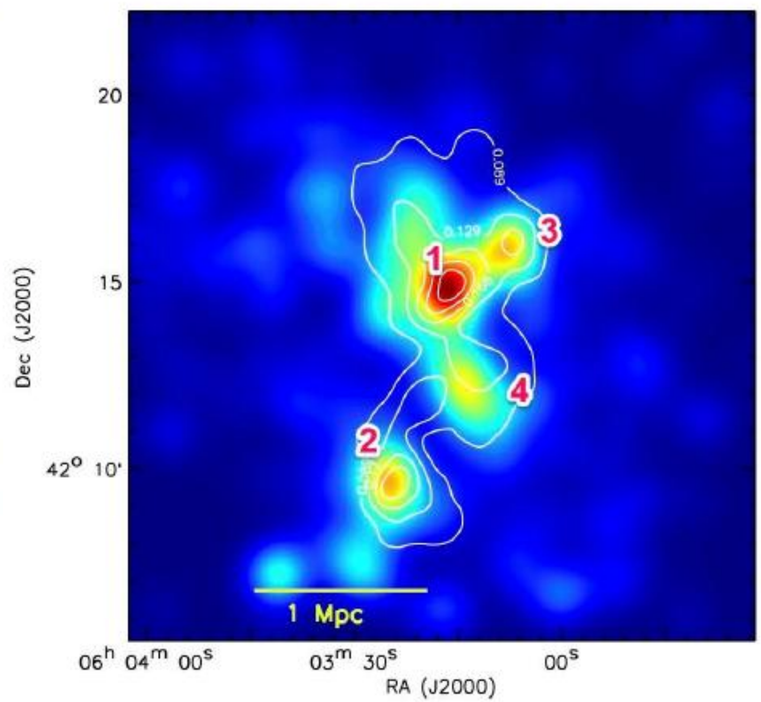


X-ray, optical, radio

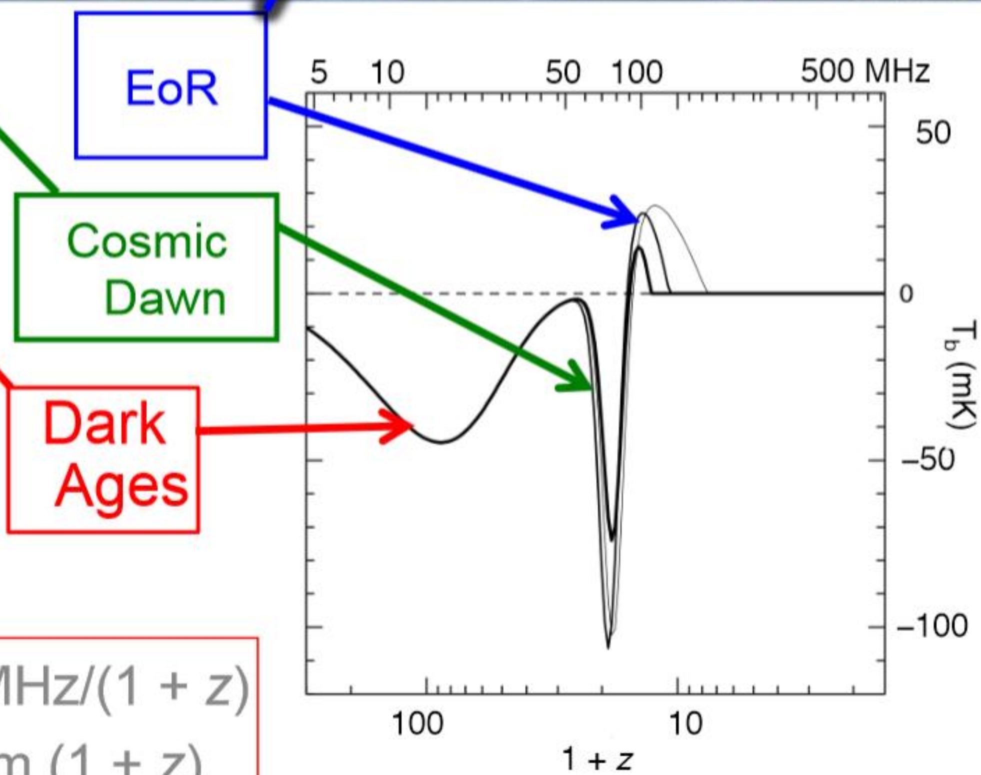
Weak lensing, determination of the total mass
~2 clusters, 6 and 2 10^{14} Mo
Coincident with the optical galaxy distributions
Jee et al 2015



RX J0603.3+4214 at z = 0.225



Epoch of Re-ionization: EoR

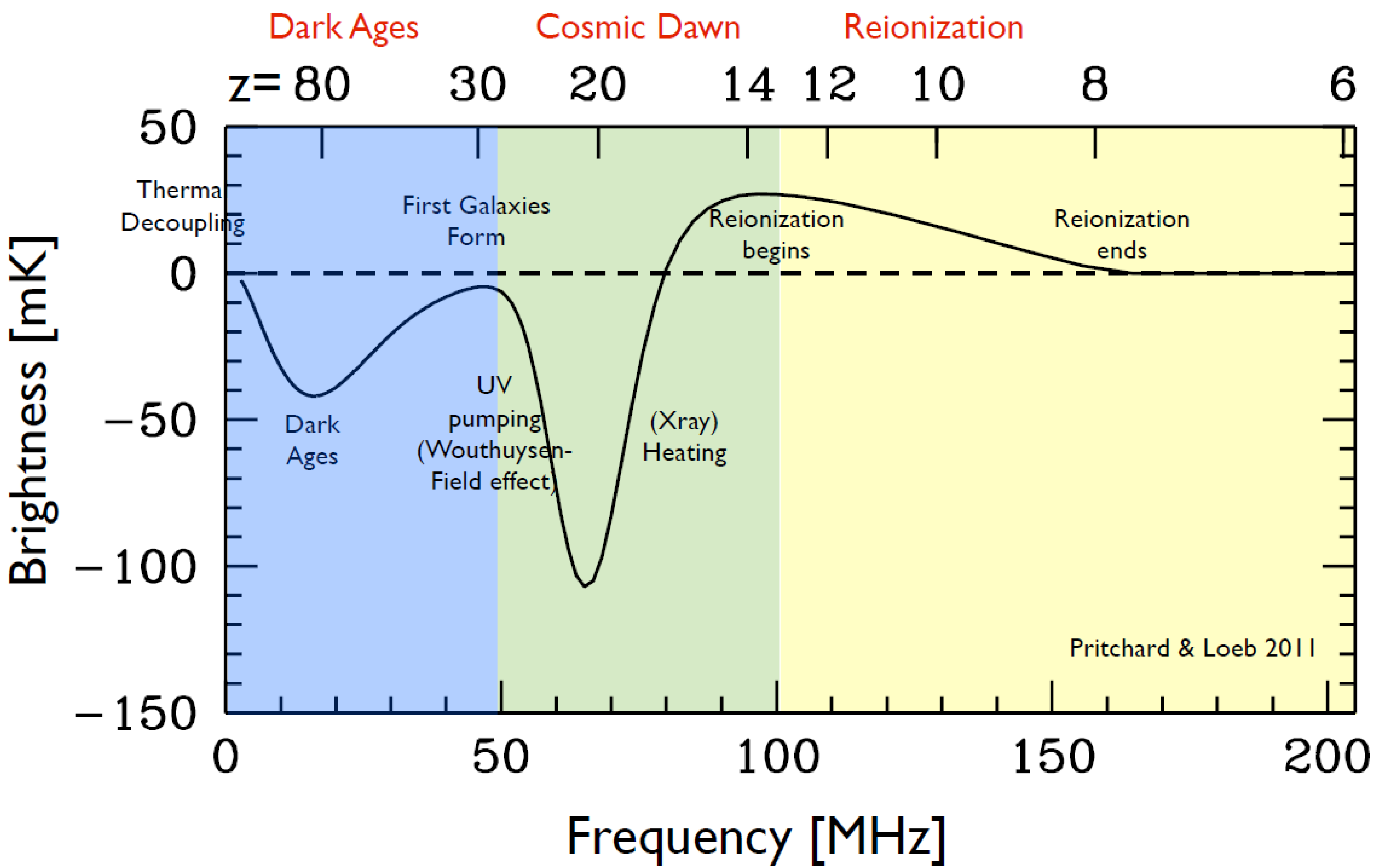


Neutral Hydrogen 21 cm
spin-flip transition
provides probe of neutral
intergalactic medium
before and during
formation of first stars

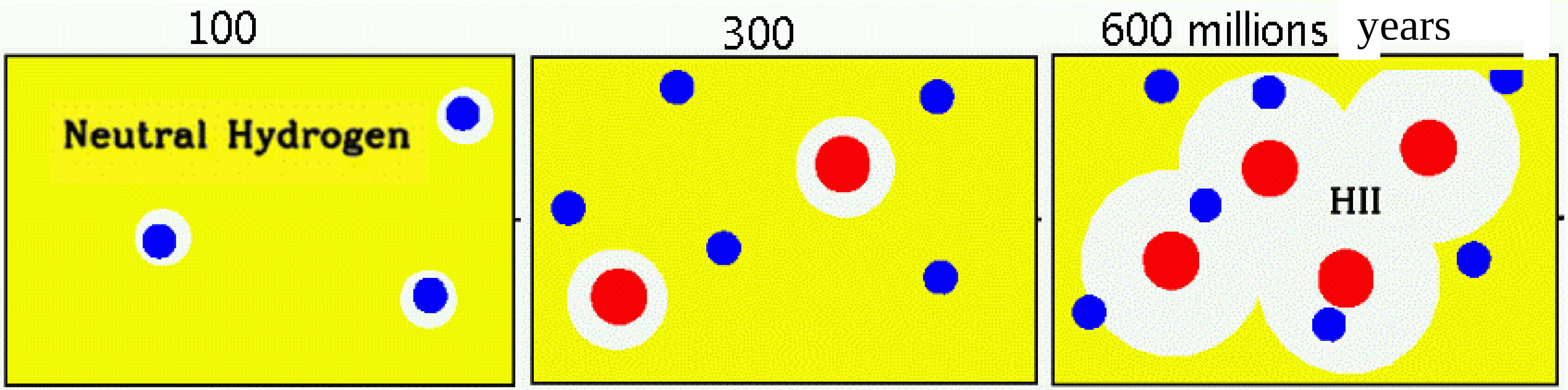
$$\nu = 1420 \text{ MHz}/(1 + z)$$
$$\lambda = 21 \text{ cm } (1 + z)$$

Brightness T_b at 21cm

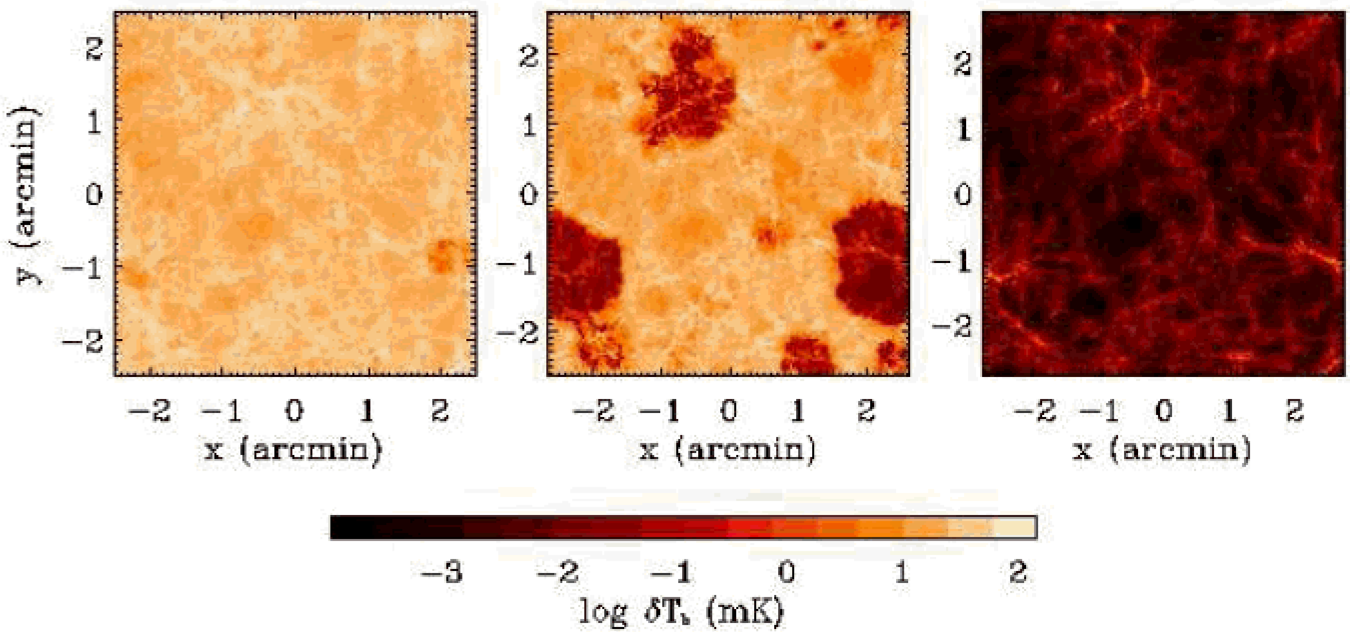
$$T_s = \frac{T_{CMB} + (y_\alpha + y_c) T_k}{1 + y_\alpha + y_c}$$



Reionization



HI tomography

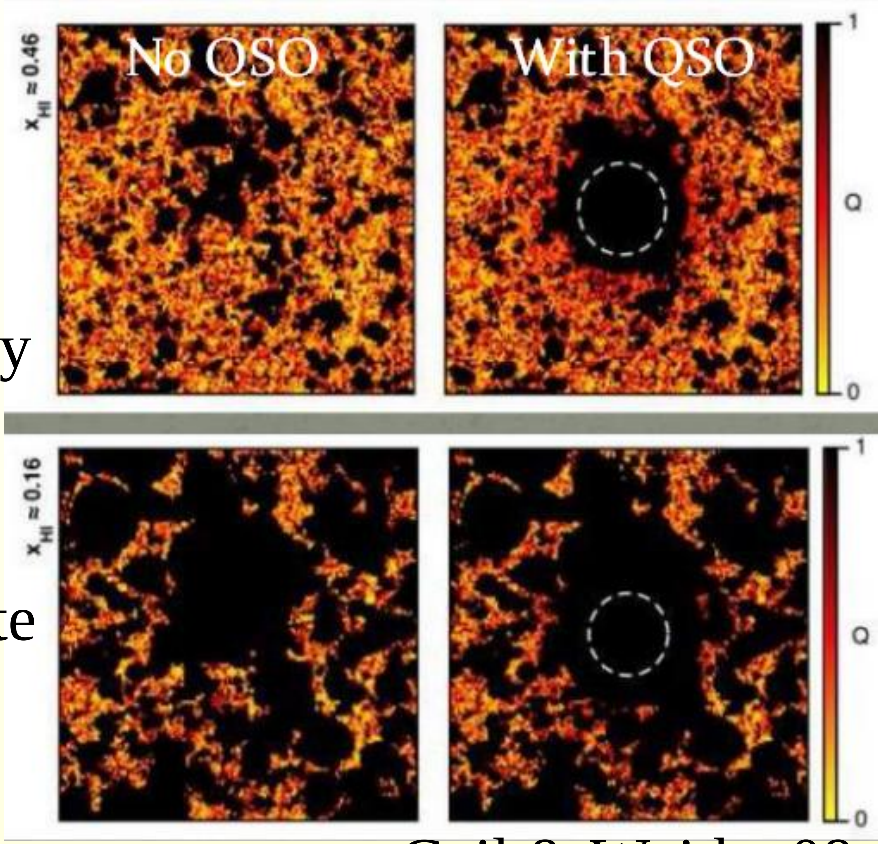


Progressive percolation of ionized zones

Simulations of EoR

Early

Late



Geil & Wyithe 08

Only simulations for now!

Synergy Euclid /SKA

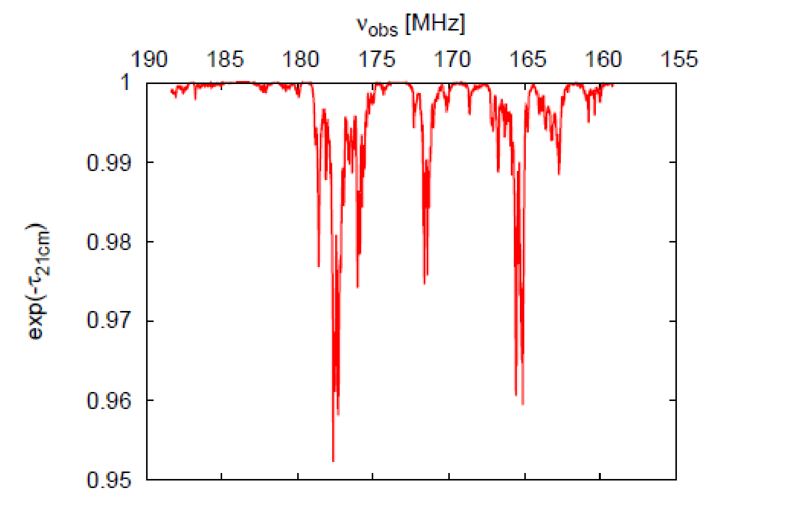
Discovery of the QSO in the EoR

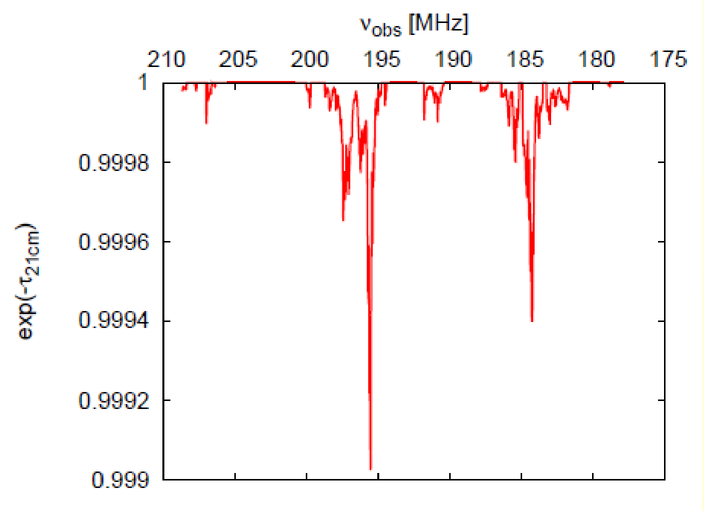
Detection of the HII region around the QSO, at high redshift

Will be studied in detail and depth by **JWST and ELT**

Also absorption studies

21cm forest: Expected spectra



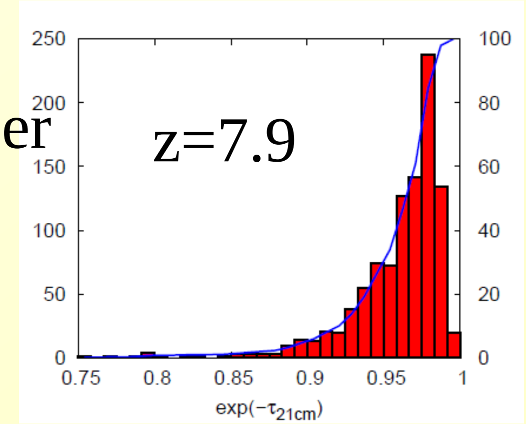


z=7.9 z=7

$<\tau_{21cm}>$ ~ 0.05 at z=7.9, and ~0.001 at z=7

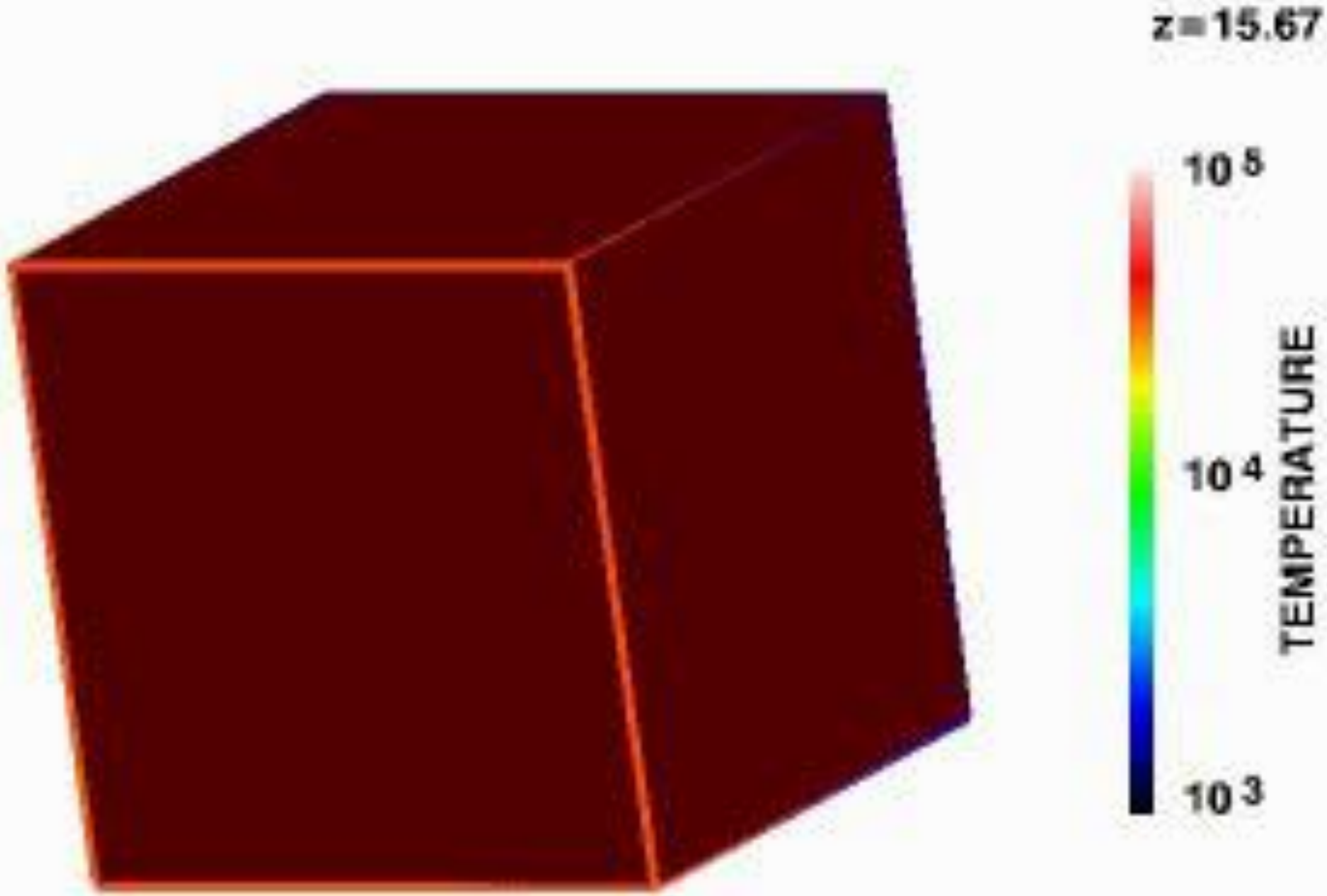
➔Not detectable at z=7
but may be at z=7.9 in 10% of cases

Number
of abs



%

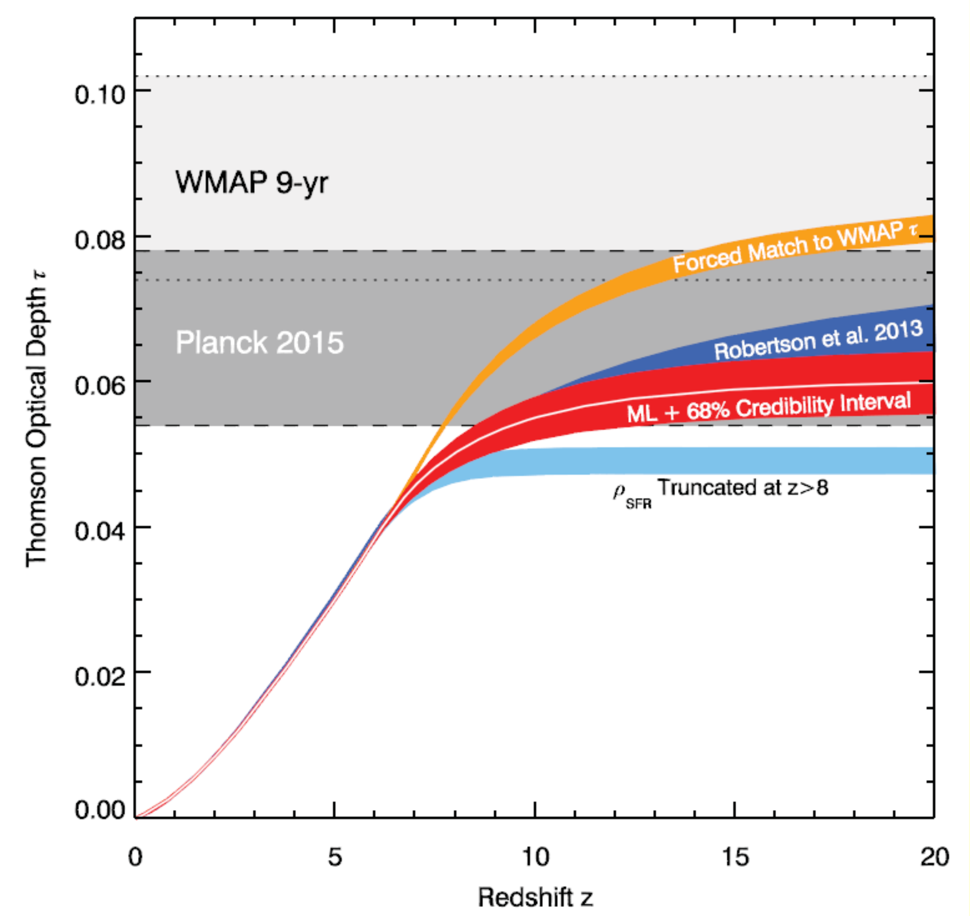
Semelin 2015

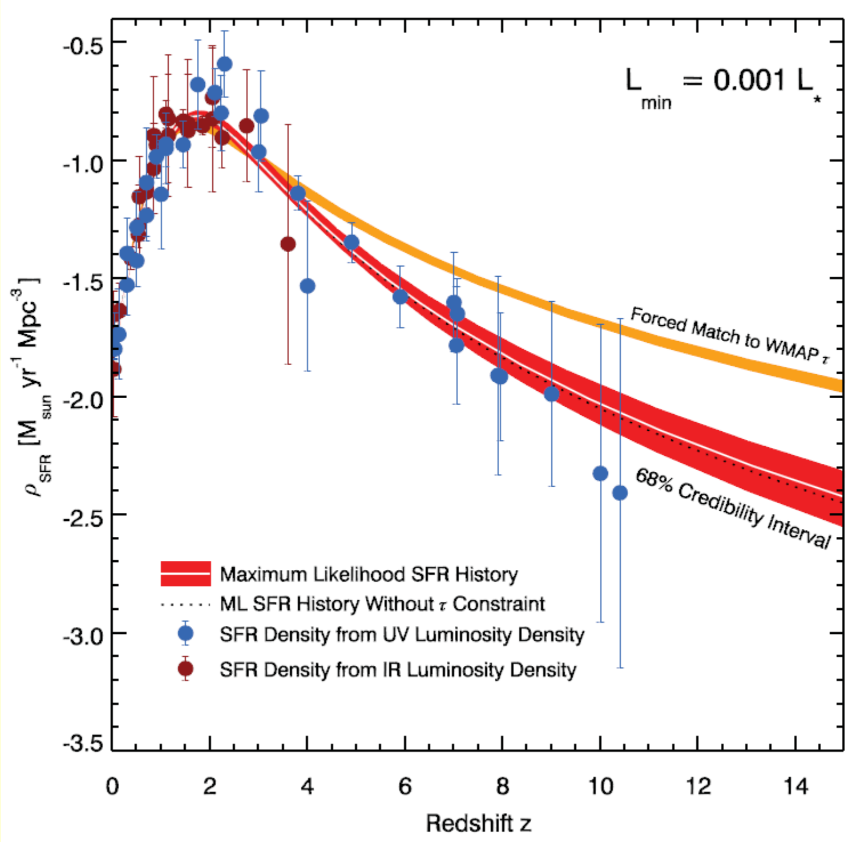

z=15.67
10 5
10 4
10 3
TEMPERATURE

New opacity from Planck

τ= 0.066±012

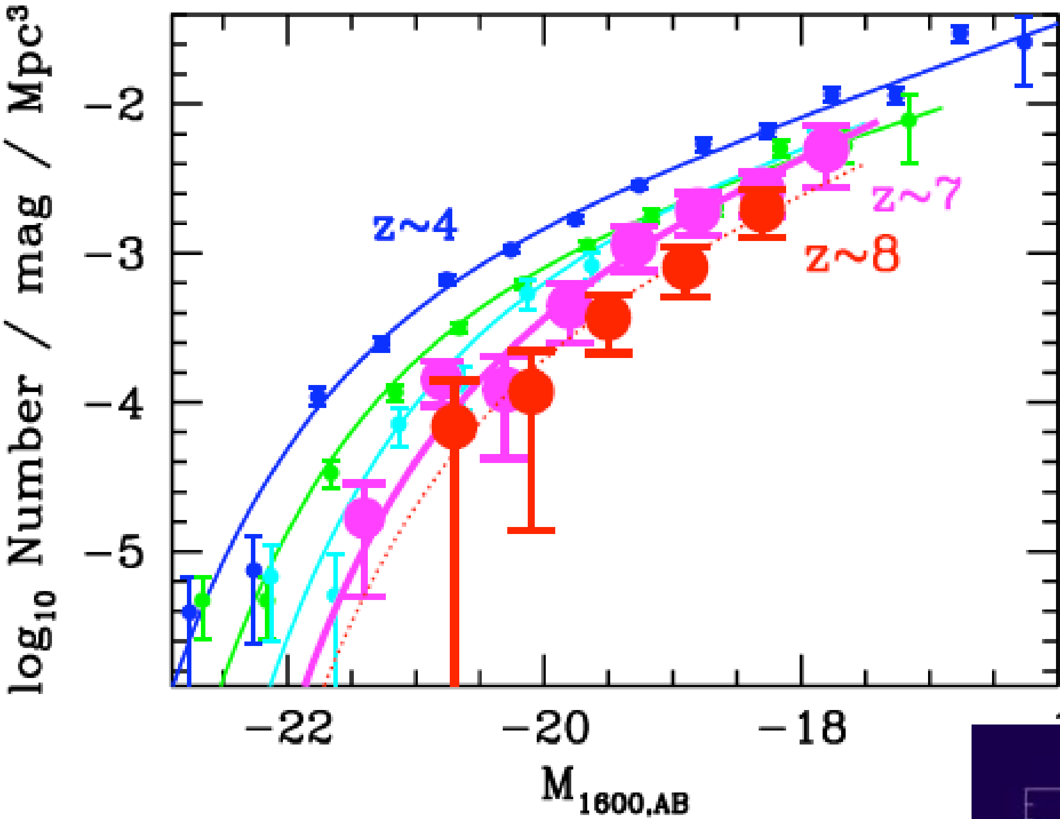
Requires less galaxies at z>8



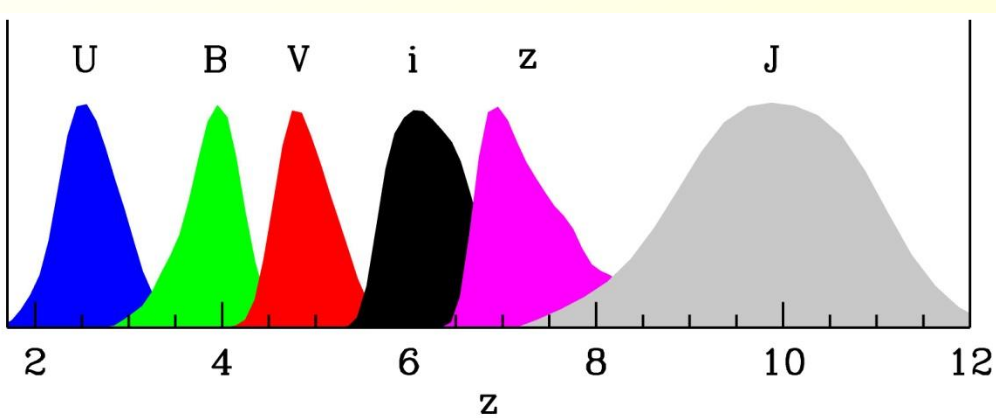


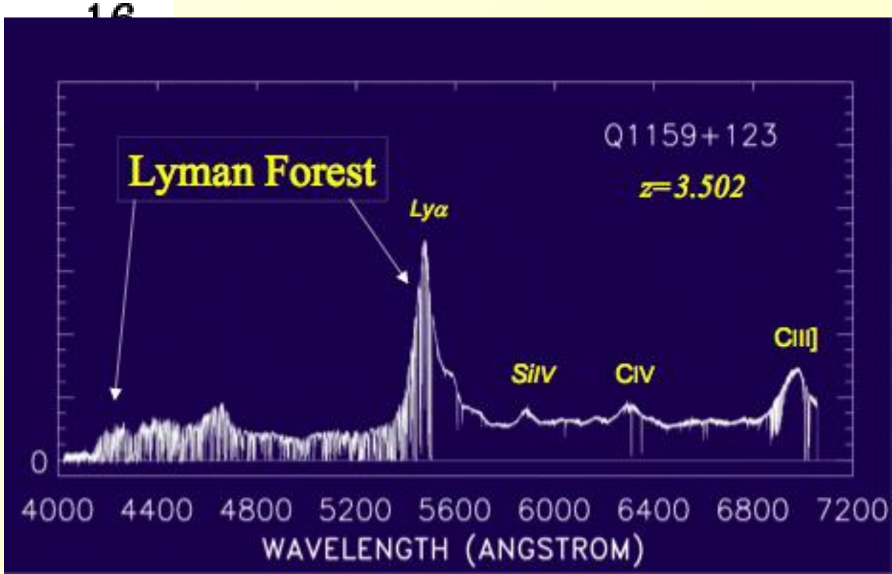
Robertson et al 2015

Are galaxies at z=7-10 able to re-ionize?



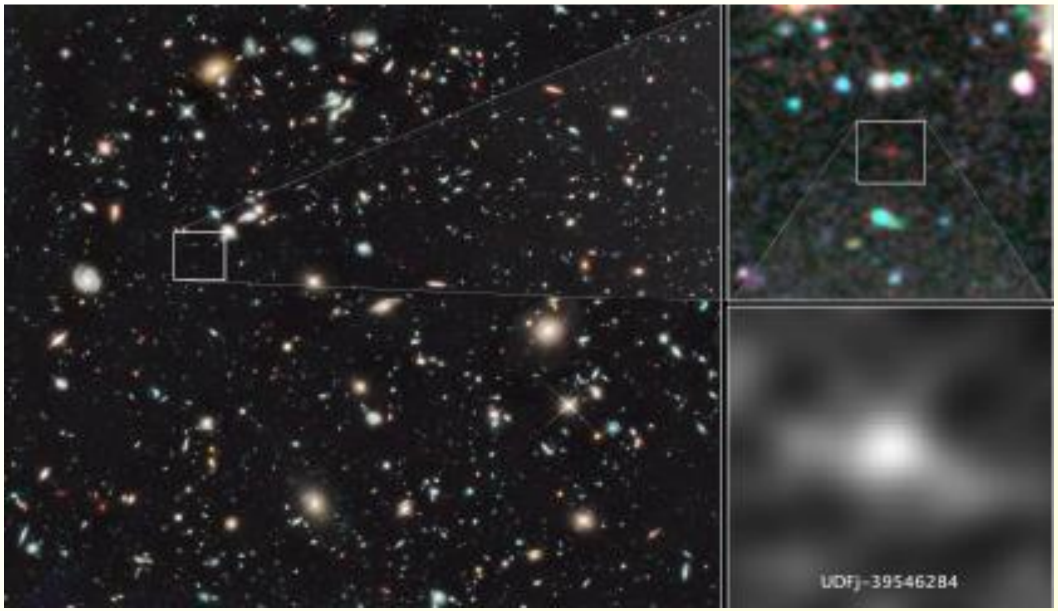
Nbre of galaxies
mag^{-1} Mpc^{-3}

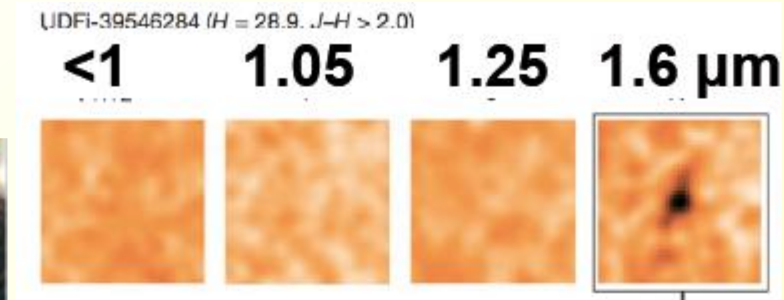




What is the first galaxy?

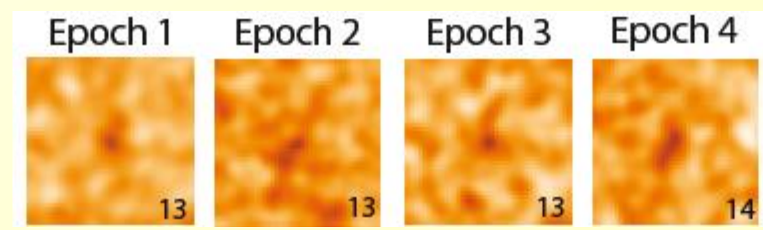
Candidates at z=10





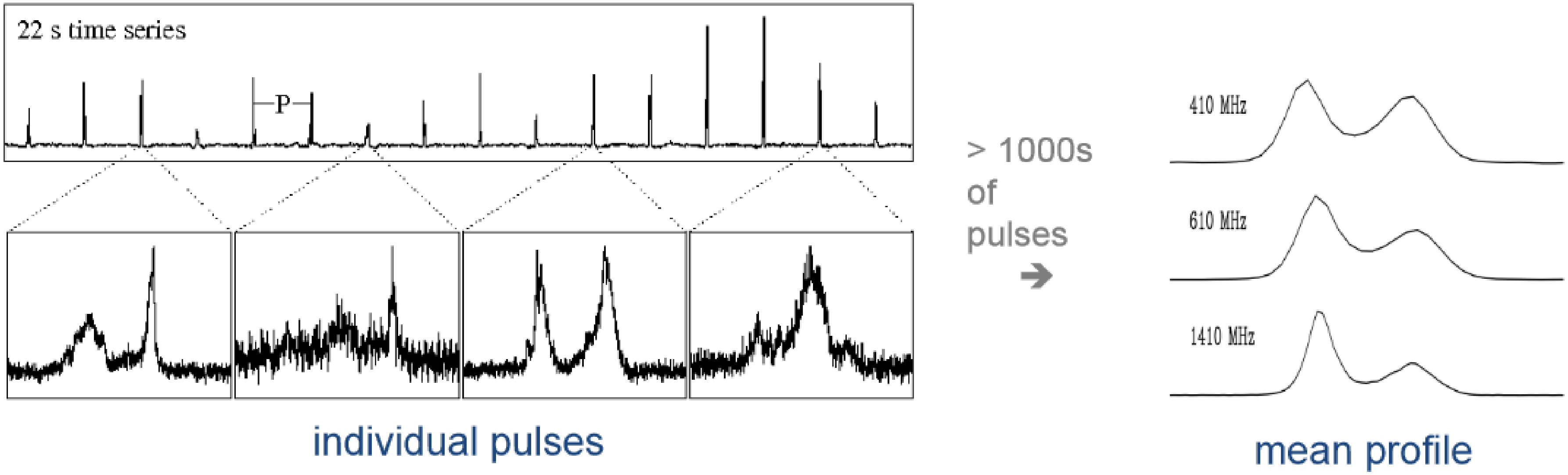
Disappears at λ=1.4 microns

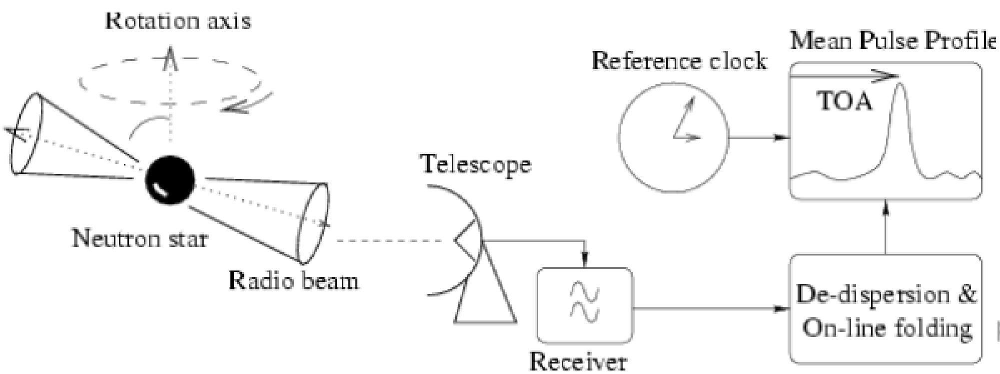
Difficult observations, at the limit
Of present telescsopes
➔JWST
6.5m, 2018



Detected in each sub-group
of observations

Pulsars: Time of Arrival (TOA)



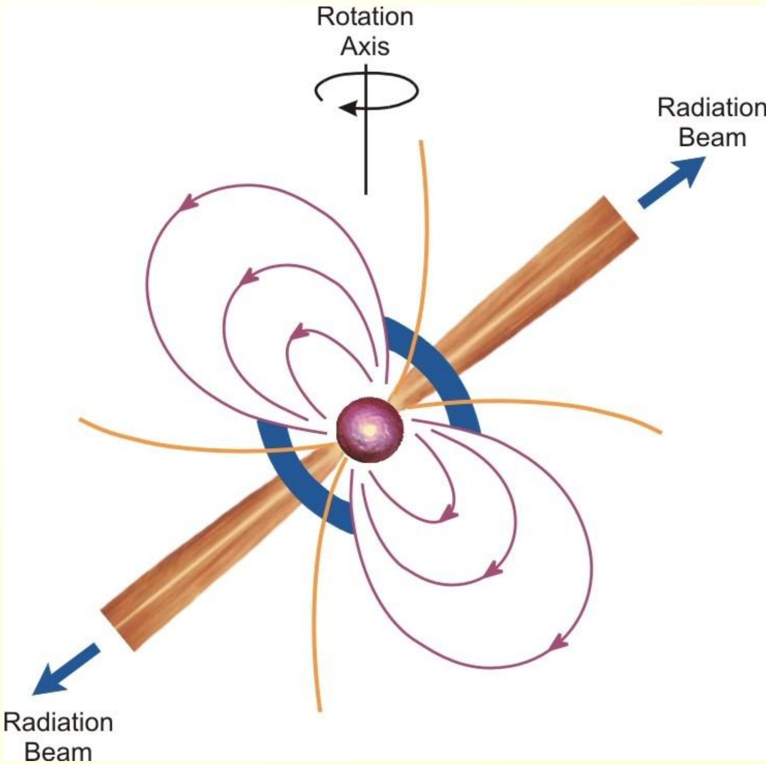


Binaries, and
Gravitational waves

From Lorimer & Kramer, *Handbook of Pulsar Astronomy*

Physics of accreting WD, NS and BH: physics of condensed matter with strong magnetic B. High sensitivity

Nature of pulsars



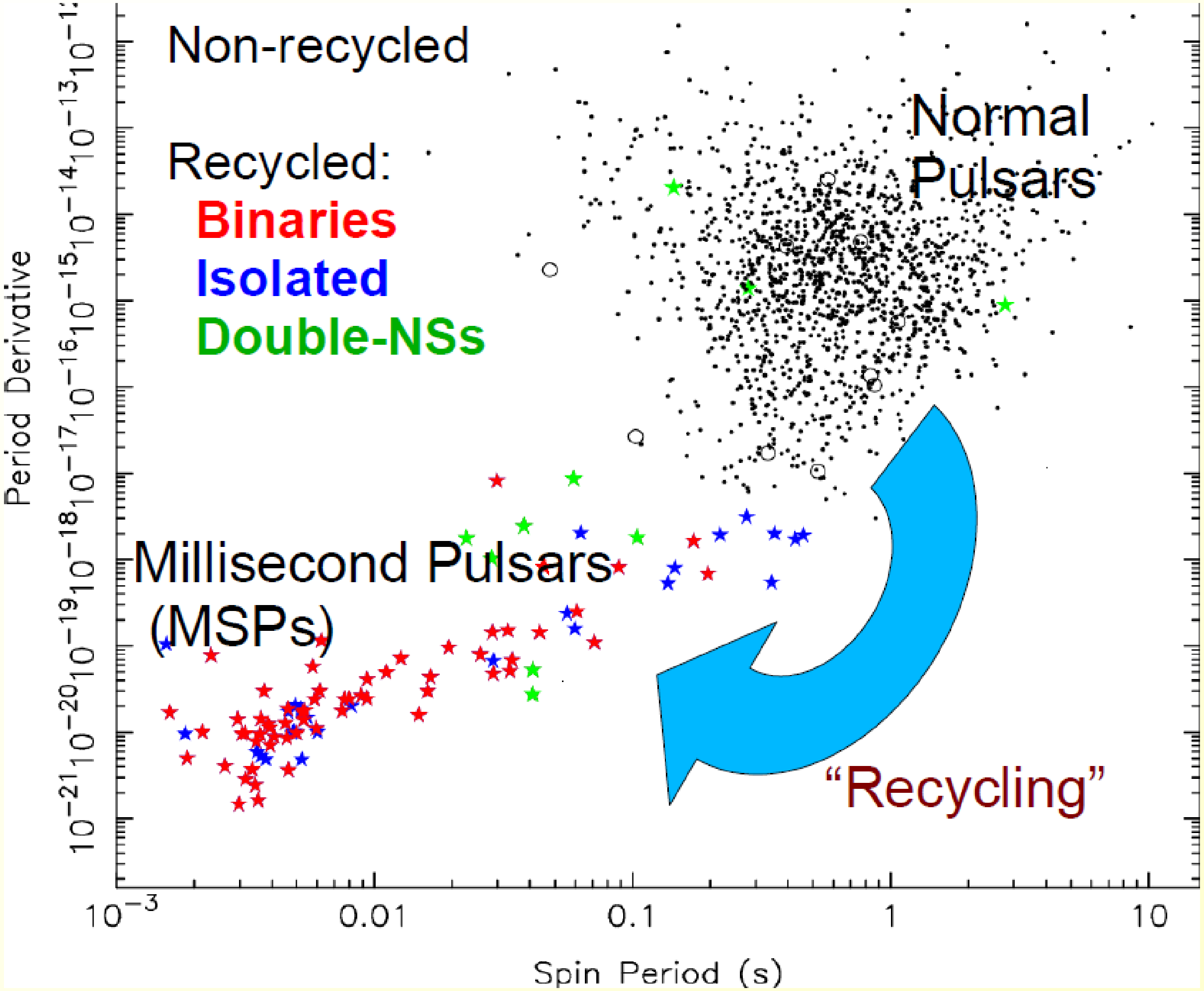
Pulsars are rotating neutron stars,
discovered by Bell & Hewish (1968)
Size ~10km, Mass~1-2 Mo,
Central density > nuclei! (10^{15}g/cm^3)
Surface gravity 10^{11} g,
Magnetic field up to B=10^{12} G

2000 « normal » pulsars known
Fast rotation with **periods 1sec** (Crab pulsar 0.03), after SN explosion or down to **milli-second (MSP)** when re-activated, in X-ray binaries

Alone the pulsar lives 100Myr, but **in a binary**, the companion can transfer mass and angular momentum, when in the giant phase, accelerating the pulsar. Since B is down to 10^8G, the spinning can live during Gyrs.

Timing of pulsars

MSPs, J0437−4715, one of the best measured has now
P= 5.7574518589879ms ±1 in the last digit (13th)
This digit increases by 1 every 1/2h



Loss by radiation and Relativistic wind

The first 6 digits keep the same for 10^3 yrs

TOA measured with μs during several yrs

➔ 14 digits

Most precise measures in Astrophysics

After one yr, astrometric precision on position, and also on spin down, and **orbit of the binary (excentricity, peri-astron, orbital period..)**

Radial velocity at mm/s (better than 1m/s for exoplanets search)

Interstellar medium (ISM) dispersion of the pulses $\Delta t \sim \nu^{-2}$

Thousands of frequency channels observed and delayed, 3GHz bandwidth

➔Petabytes of data (several dispersions should be tried for discovery)

When the binary is edge-on: case of J1614-2230

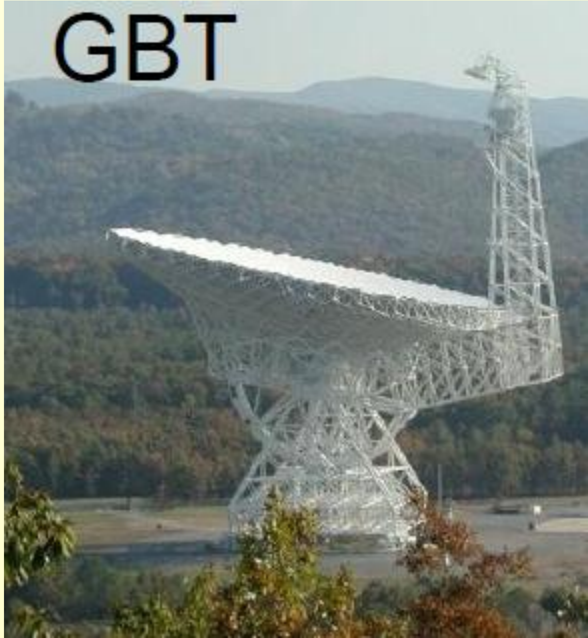
Gravitational delay when MSP behind white dwarf

➔ Shapiro delay

8.7 days orbit, 30 μs delay of the pulses!

Observed with GBT-GUPPI

GPU and FPGA to process the signal

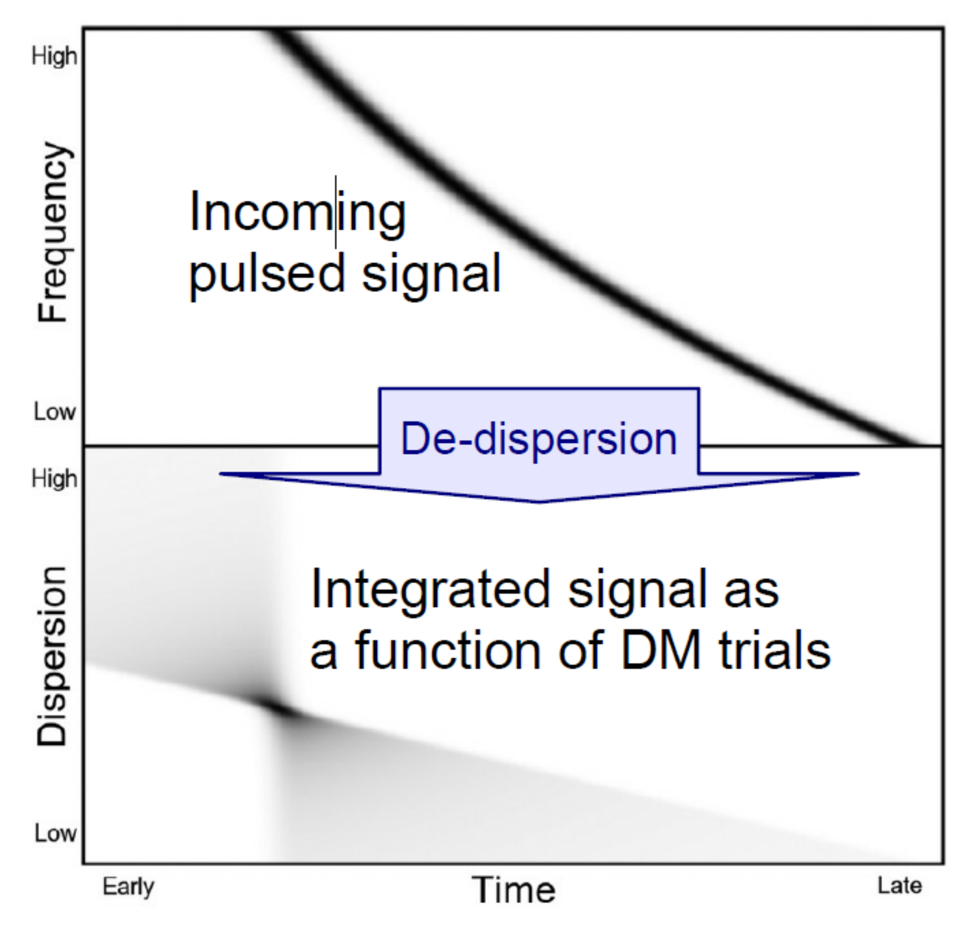


The dispersion problem

$\Delta t \sim DM\nu^{-2}$
(DM = Dispersion Measure)

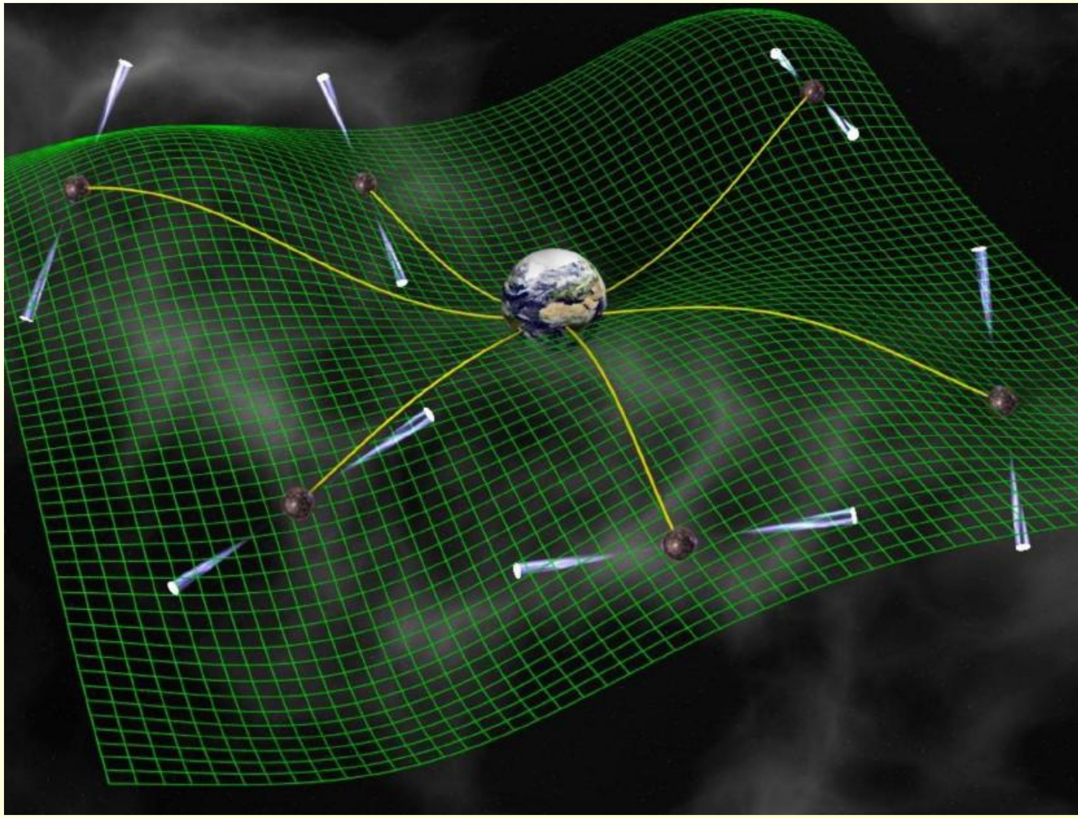
Barsdell et al 2012

- Need ~10^4 frequency channels
- DM for undiscovered pulsar is unknown
- Must search over ~few x 10^4 trial DMs!
- This multiplies data rate by factor of few
- ~0.1 Pops for SKA1
- De-dispersion is very I/O intensive



Gravitational waves

PTA: pulsar timing arrays. Monitoring several MSP
GW have nanoHz frequencies (λ ~light-yr)
Correlation between the TOA
of several pulsars
Will trace space streching

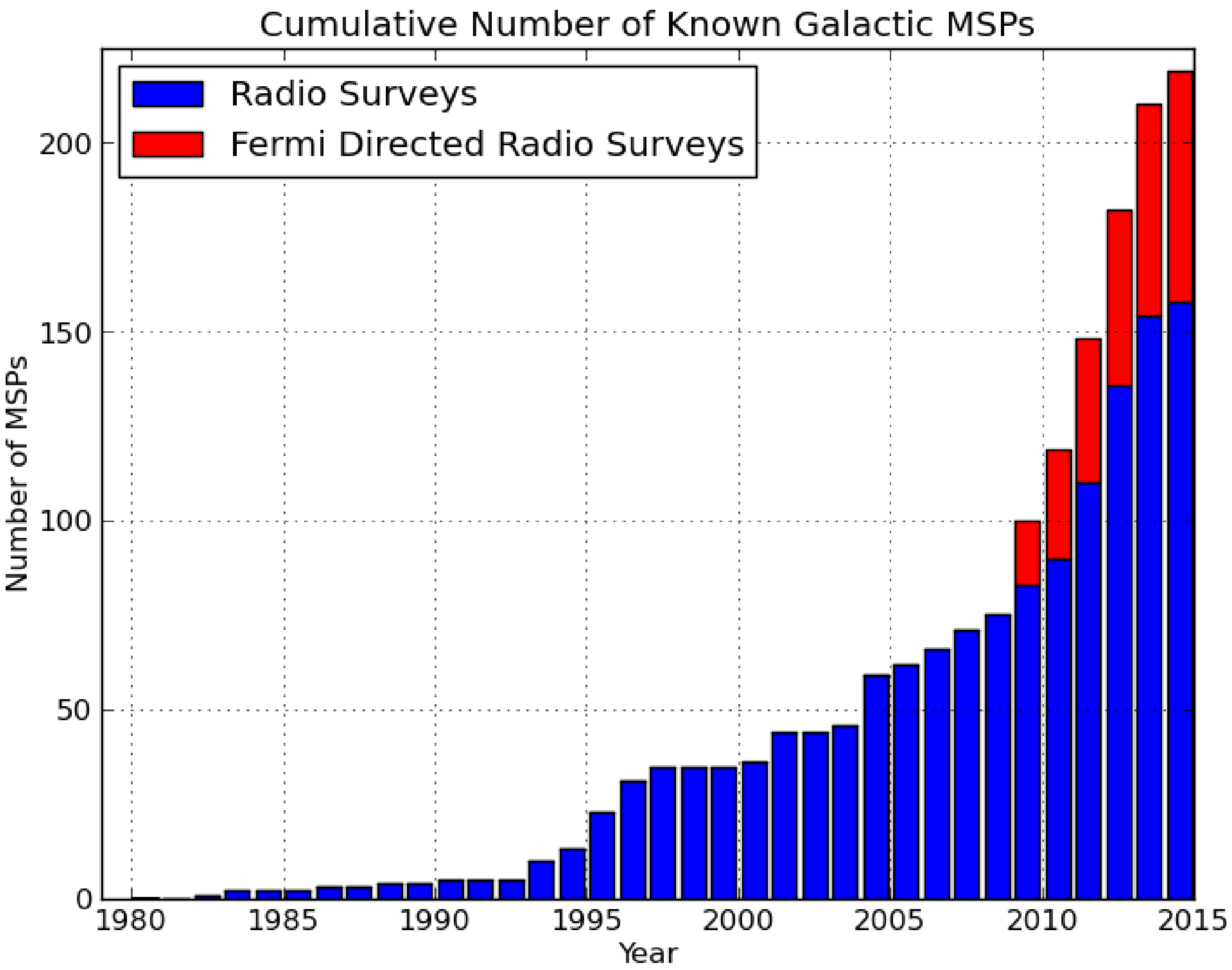


➔detect GW before LIGO ?

GW coming from merger of
black holes, if nearby
Will be seen in other λ

Or noise due to the ensemble of
mergers (stochastic background)

A bright future with the radio observatories: SKA and precursors



Nbeams=
$(Dtot/d)^2$
=4000
or To/s data

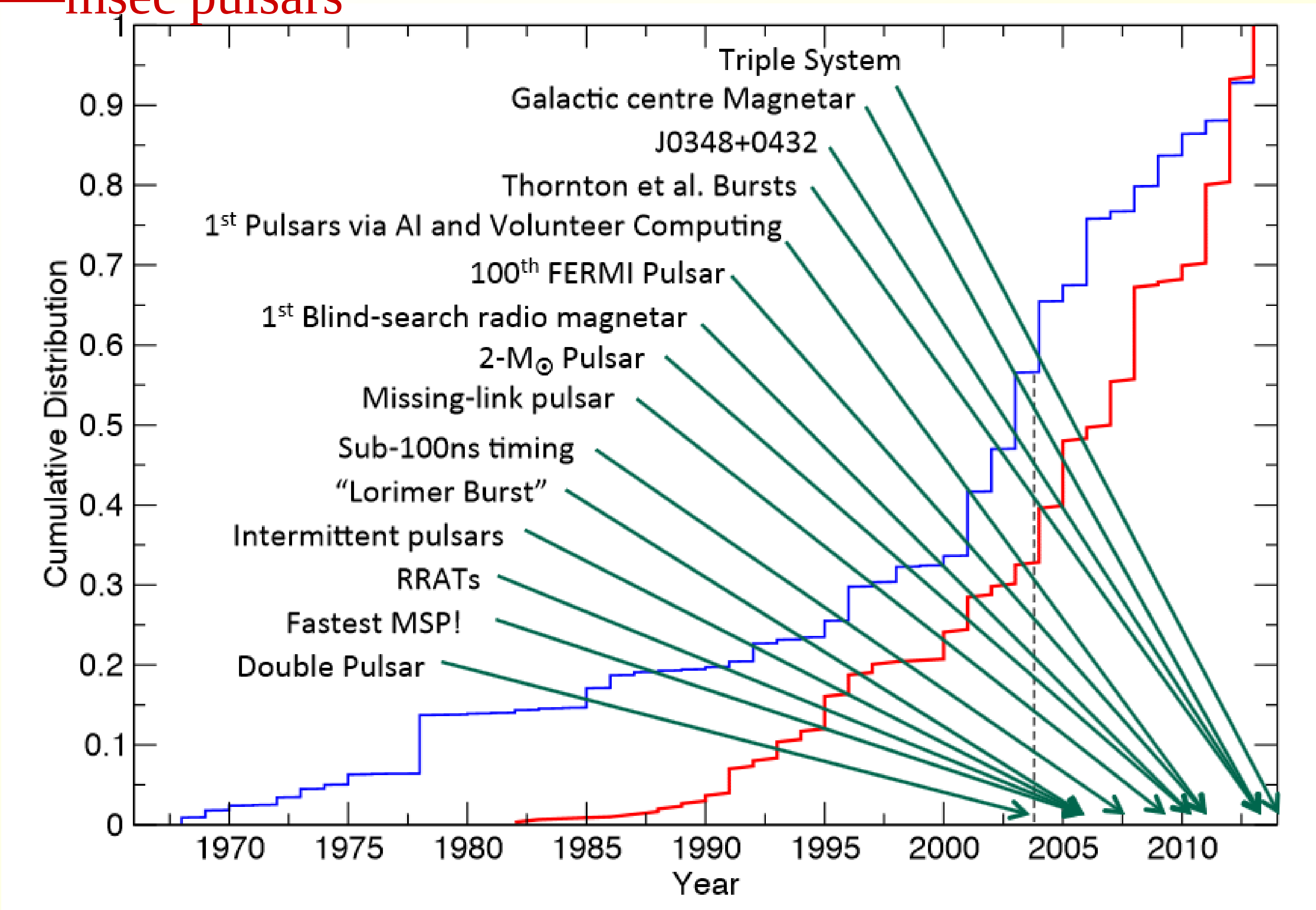
Cannot record, but
Process on-time

Cannot re-analyse
➔ Re-observe

History of discoveries

—Normal pulsars
—msec pulsars

Numbers will be x **more than 10 by SKA**

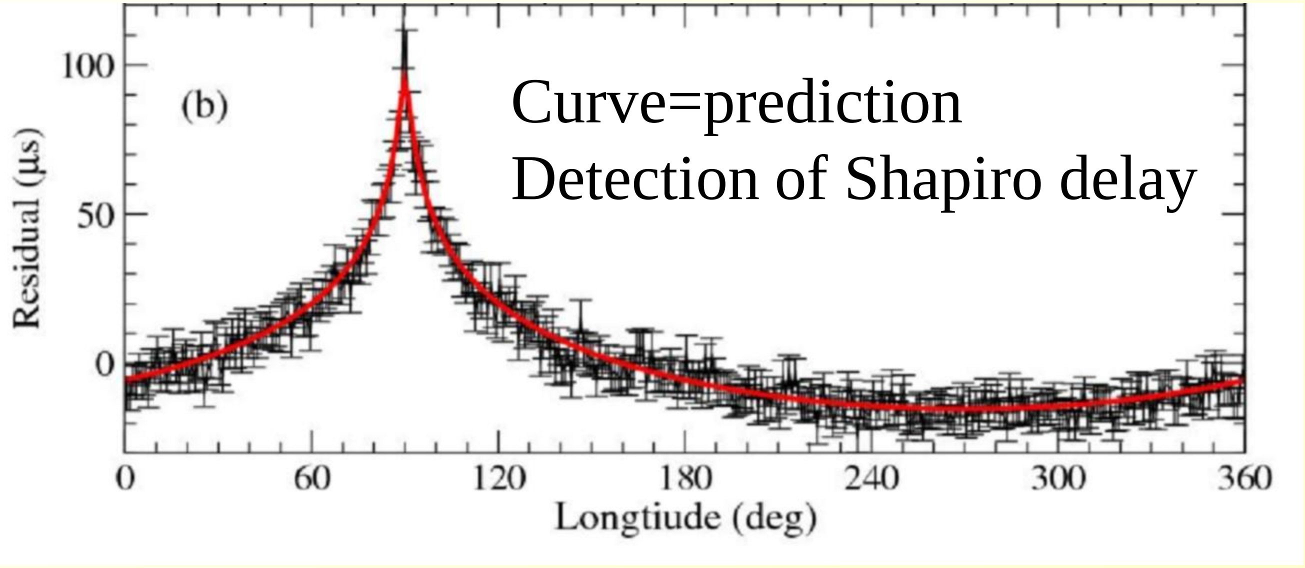


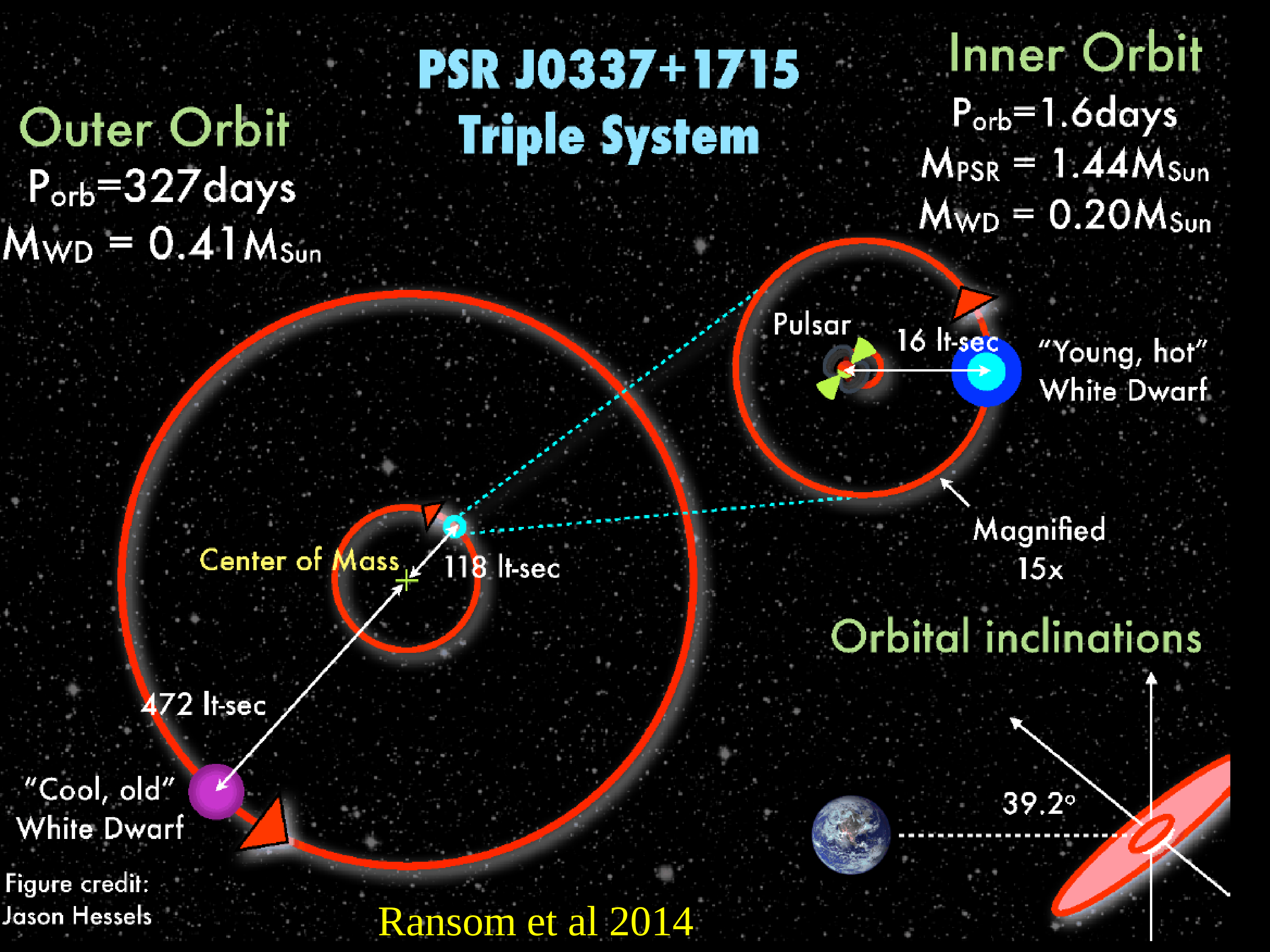
Tests of General Relativity

Gravity in strong fields: PSR-Neutron star, PSR-black hole
Was Einstein right?, Cosmic Censorship Conjecture
(i.e. Naked singularities), No-hair theorem

Double pulsars timing: 0.05% test of general relativity in "strong"-field (gravitational delay)

Kramer et al 2006, Science PSR J0737-3039A/B

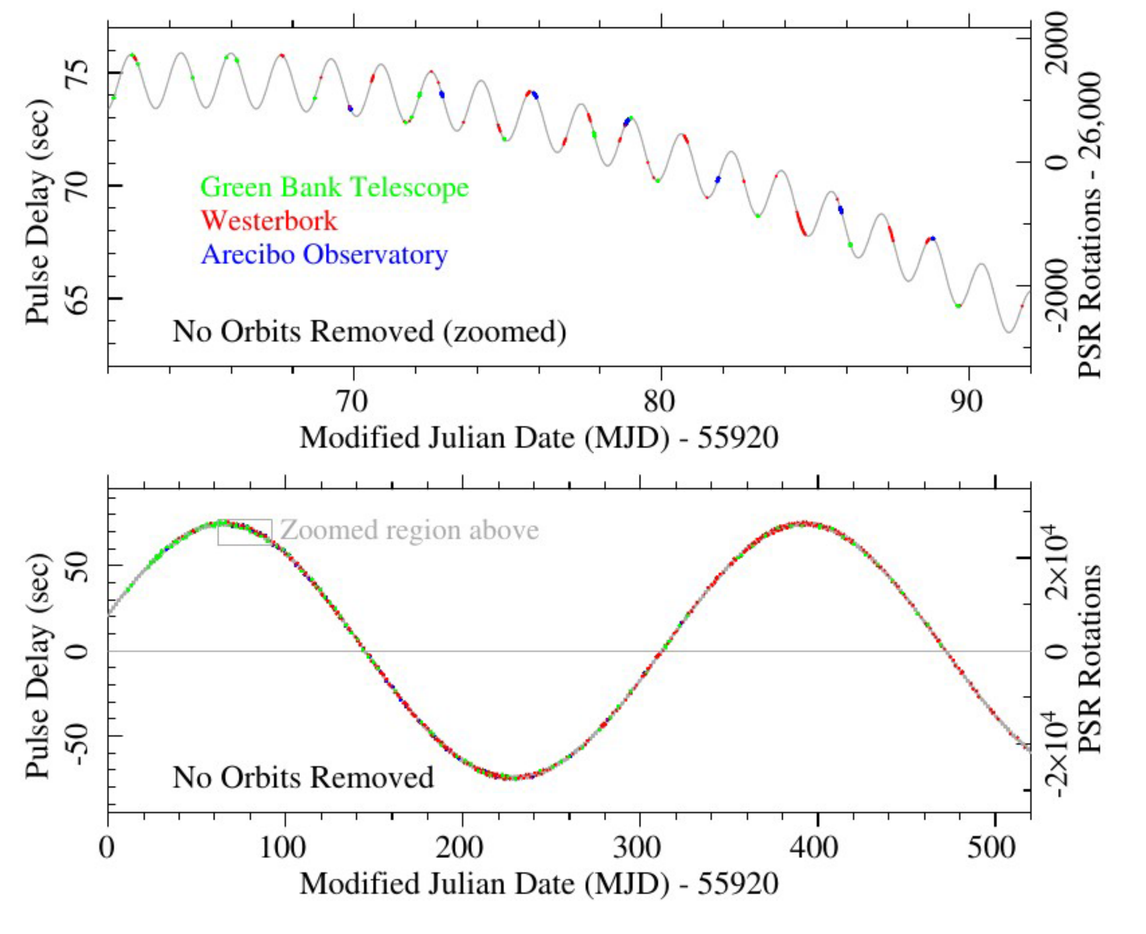


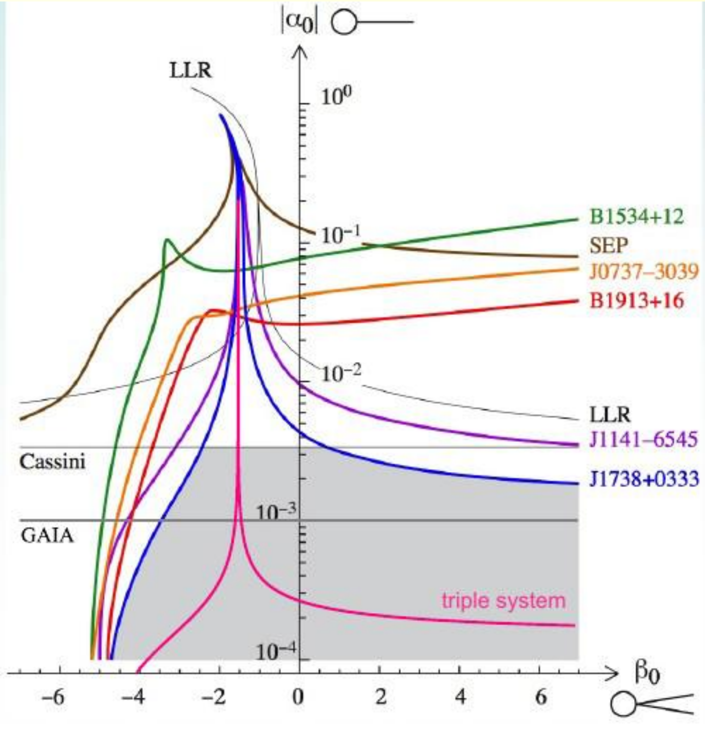

PSR J0337+1715
Triple System
Outer Orbit
P_{orb}=327days
M_{WD} = 0.41M_{Sun}
Inner Orbit
P_{orb}=1.6days
M_{PSR} = 1.44M_{Sun}
M_{WD} = 0.20M_{Sun}
Pulsar
16 lt-sec
"Young, hot" White Dwarf
Magnified 15x
Center of Mass
118 lt-sec
472 lt-sec
"Cool, old" White Dwarf
Orbital inclinations
39.2°
Figure credit: Jason Hessels
Ransom et al 2014

Precise data from the triple system

Allows to test the **Strong Equivalence Principle**
➔verified in strong gravity also

Other scalar-tensor theories
GR: α0=β0=0

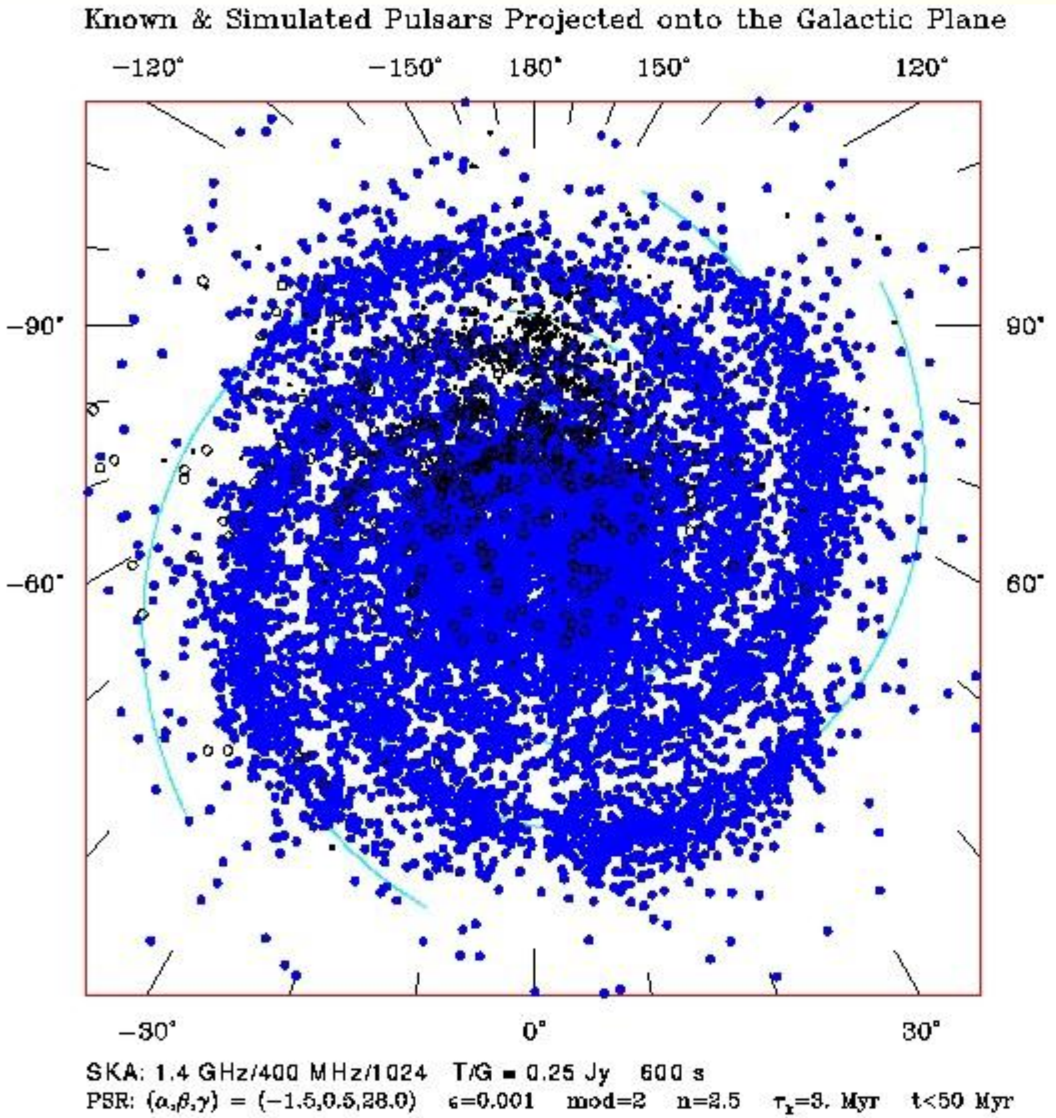




Freire et al 2012
Antoniadis et al 2013

Pulsars with SKA

J Cordes, 2004



MW: 30000 PSR, 10^4 MSP
~20,000 potentially visible normal pulsars, MSPs and RRATs = **Rotating Radio Transients** *(irregular, nulling, might be more abundant?)*

- SKA1 has the potential to find a large fraction (~50%?) of these pulsars

Original Goal

Project (~2020-30) for a giant radiotelescope
in the centimetre-metre λ range

• **one square kilometre collecting surface**

50-100 x more sensitive than present radio telescopes
for *spectral line* observations

1000 x more sensitive than present radio telescopes
for *continuum* observations

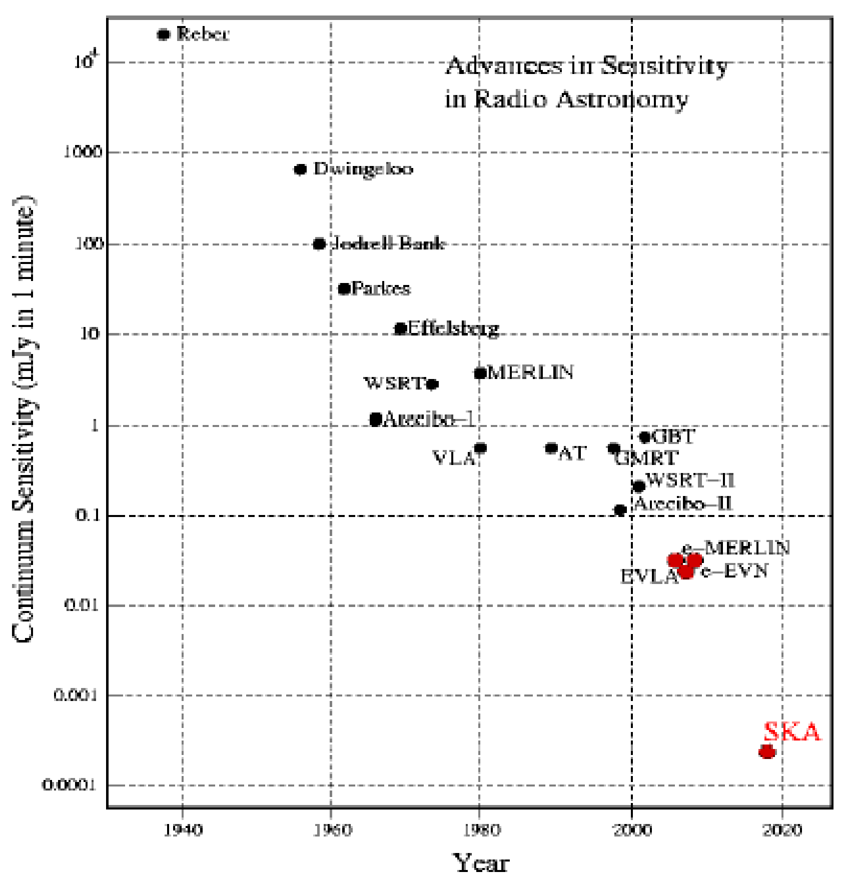
• frequencies: 70MHz – 25 GHz (λ 1.2cm – 4m)

• field of view: 1 (→ 100?) square degrees at λ 21 cm / 1.4 GHz
8 independent fields of view

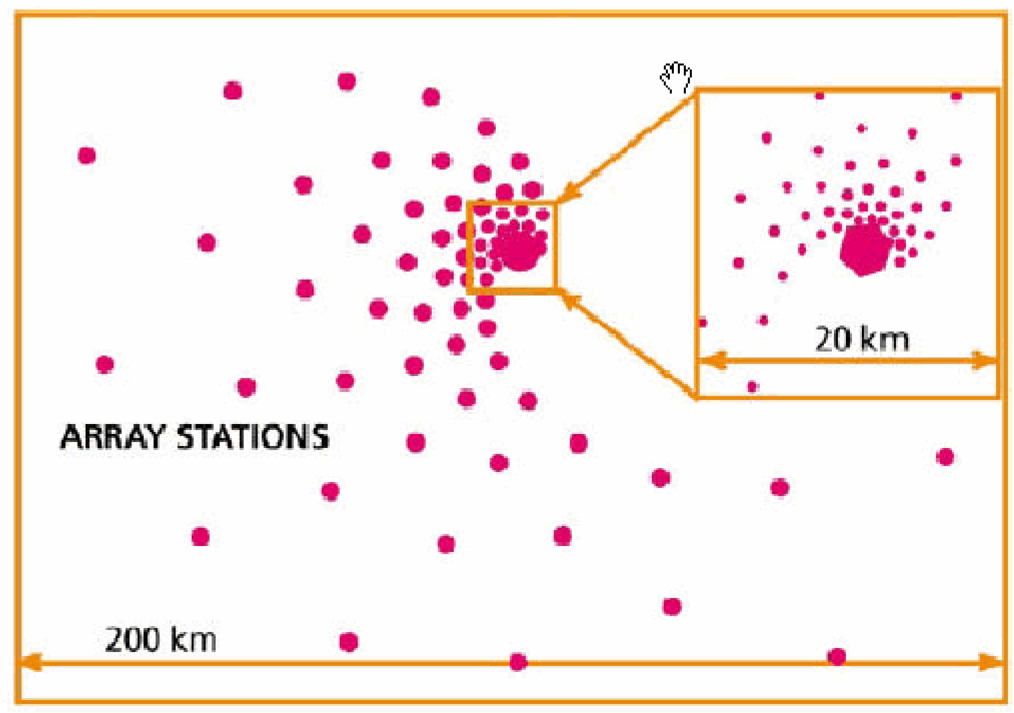
• angular resolution: 0.01 arcsec at λ 21 cm / 1.4 GHz

→ baselines up to ~ 3000 km

SENSITIVITY

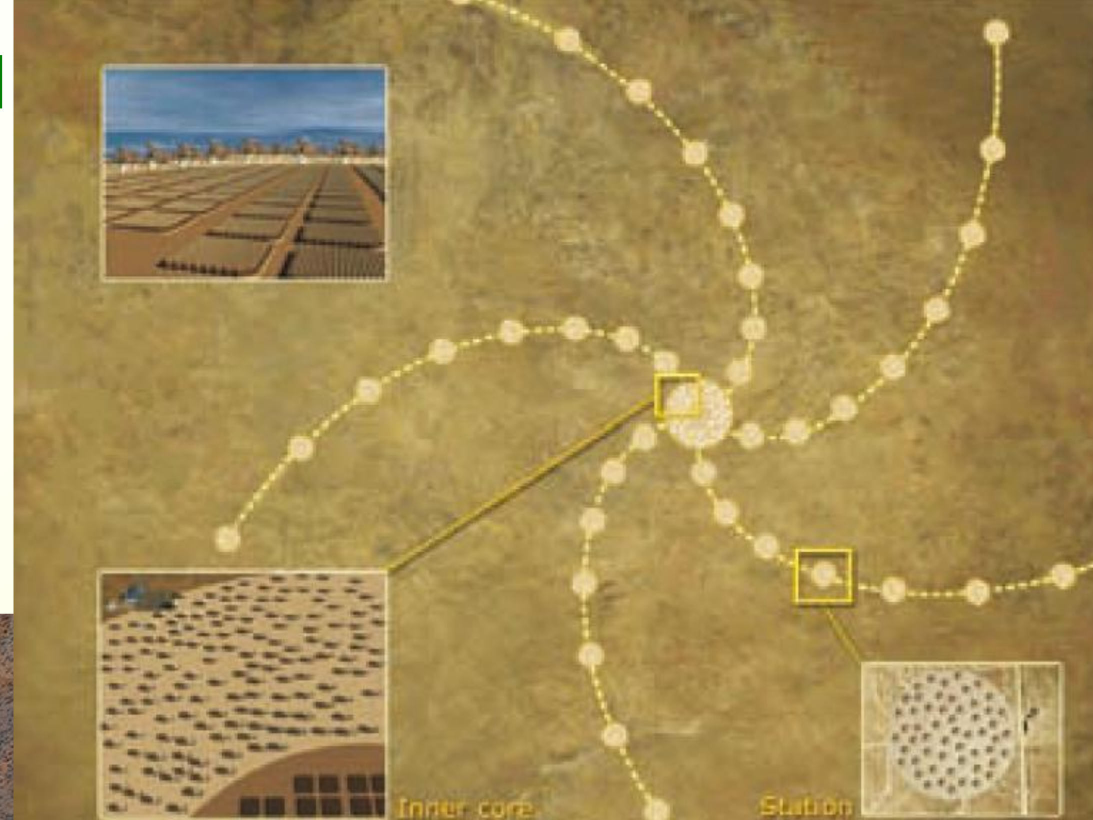


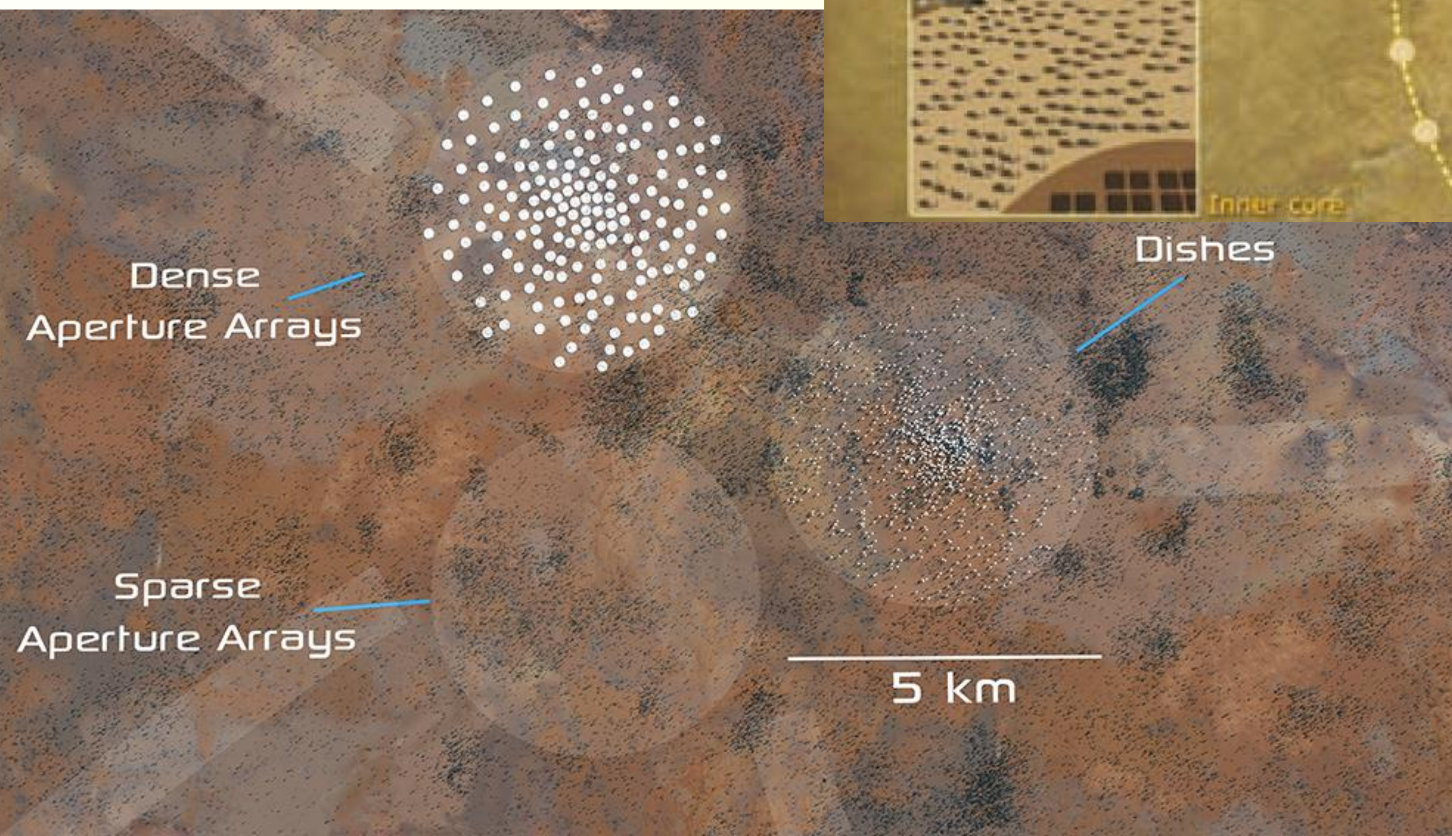
Point source sensitivity of 10 nano-Jy in 8hours



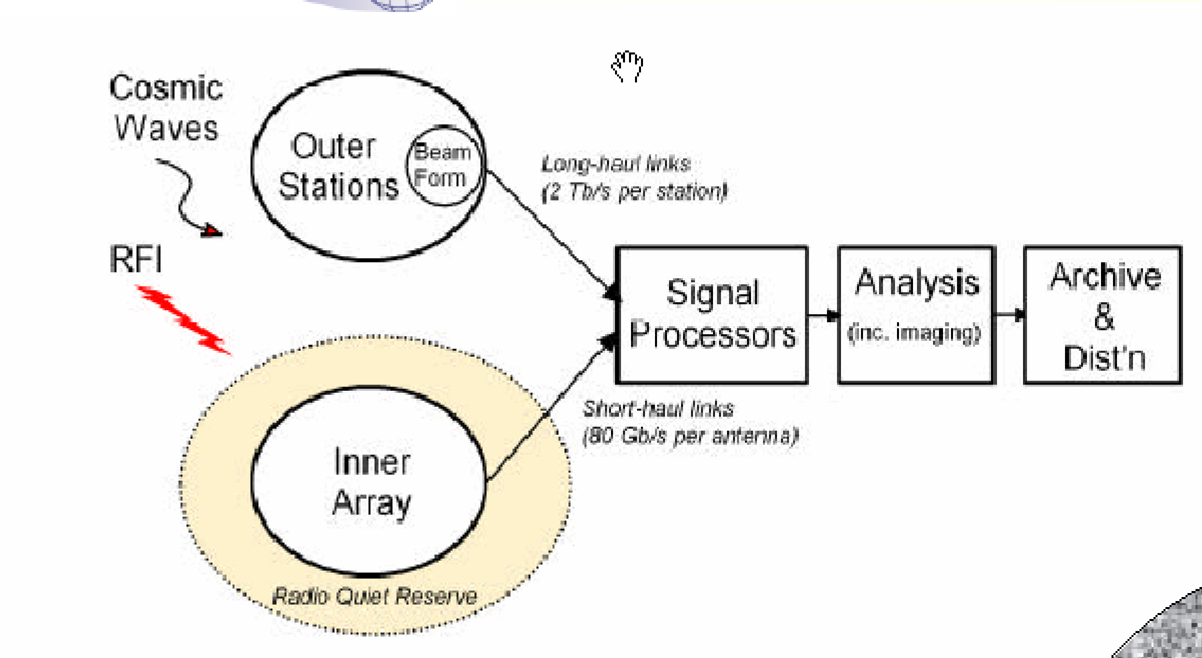
CONFIGURATION

Presently foreseen disposition of the core

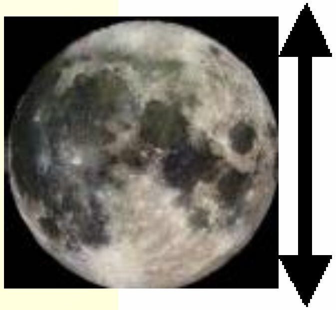


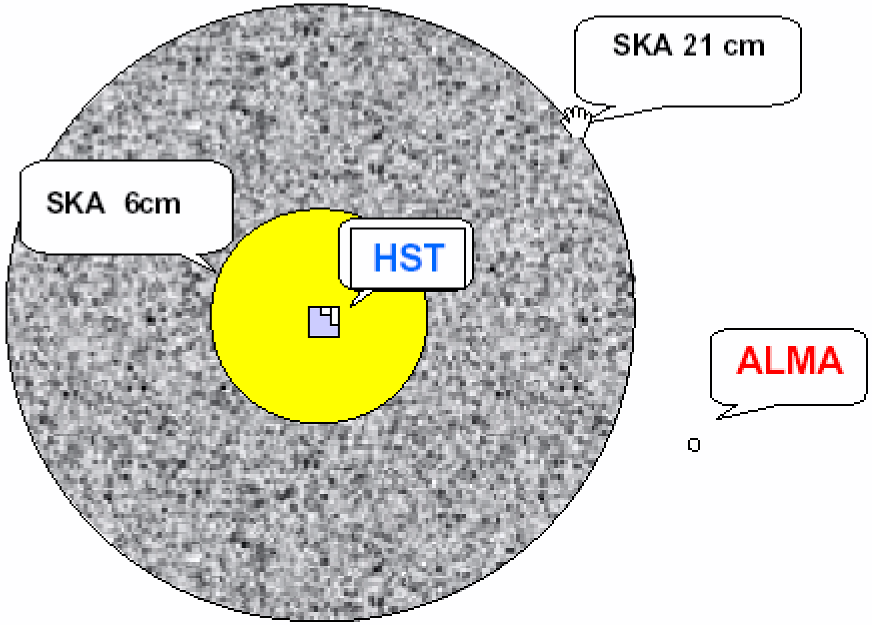


Field of View

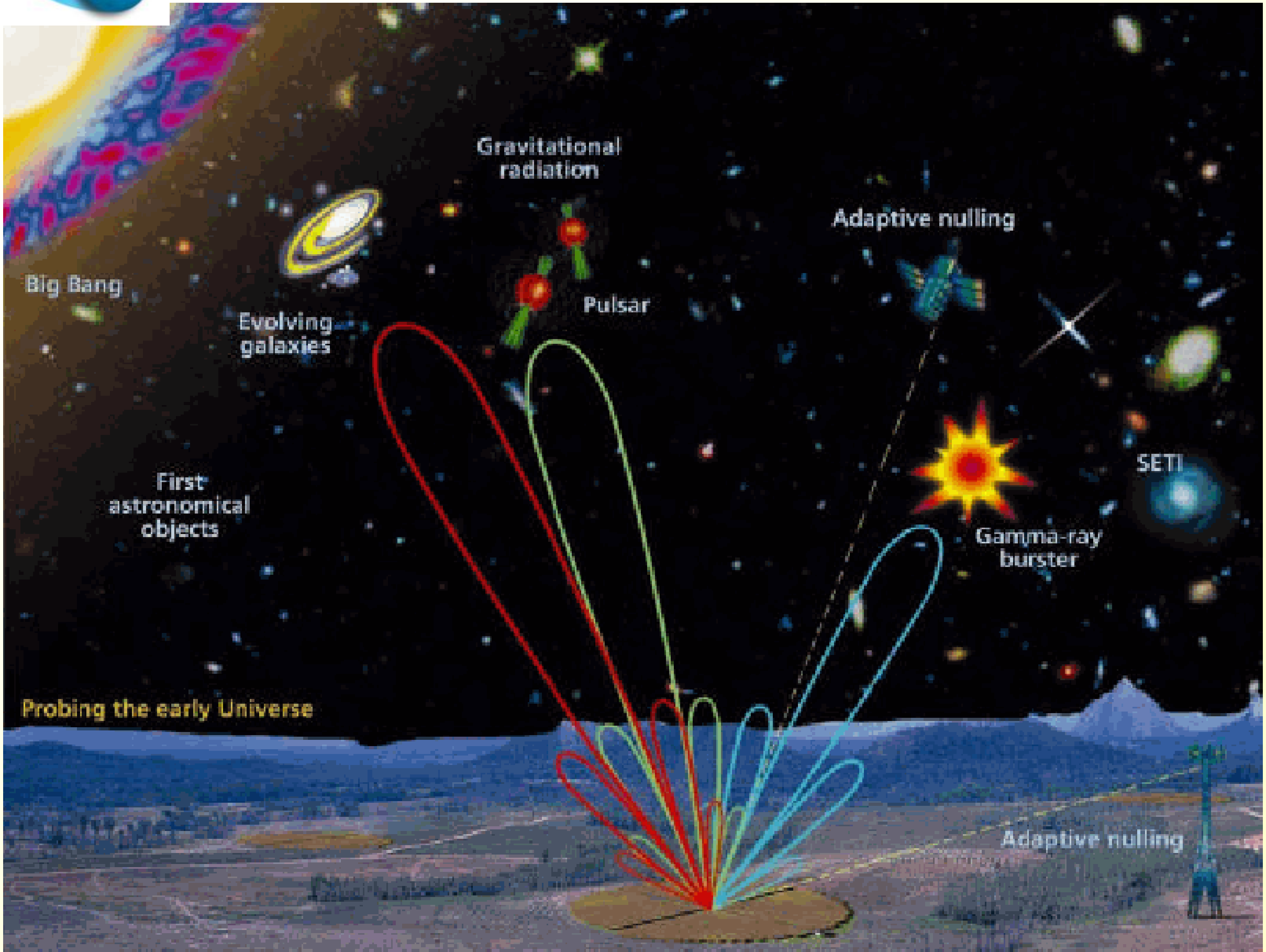


At least 1 square degree
Goal 50-100 sq deg.





Multi-Beam

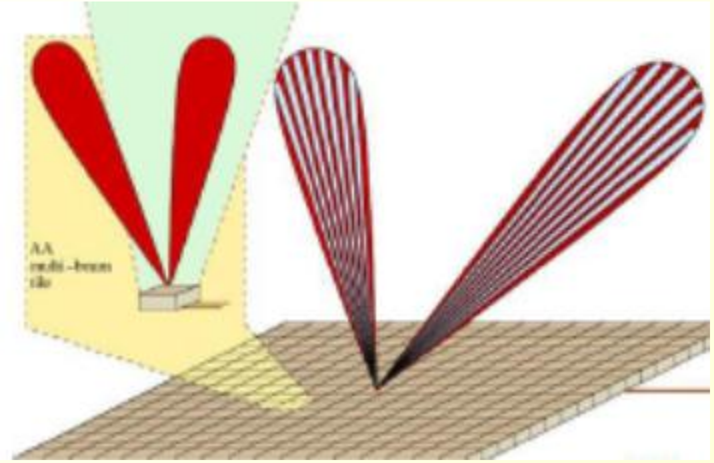


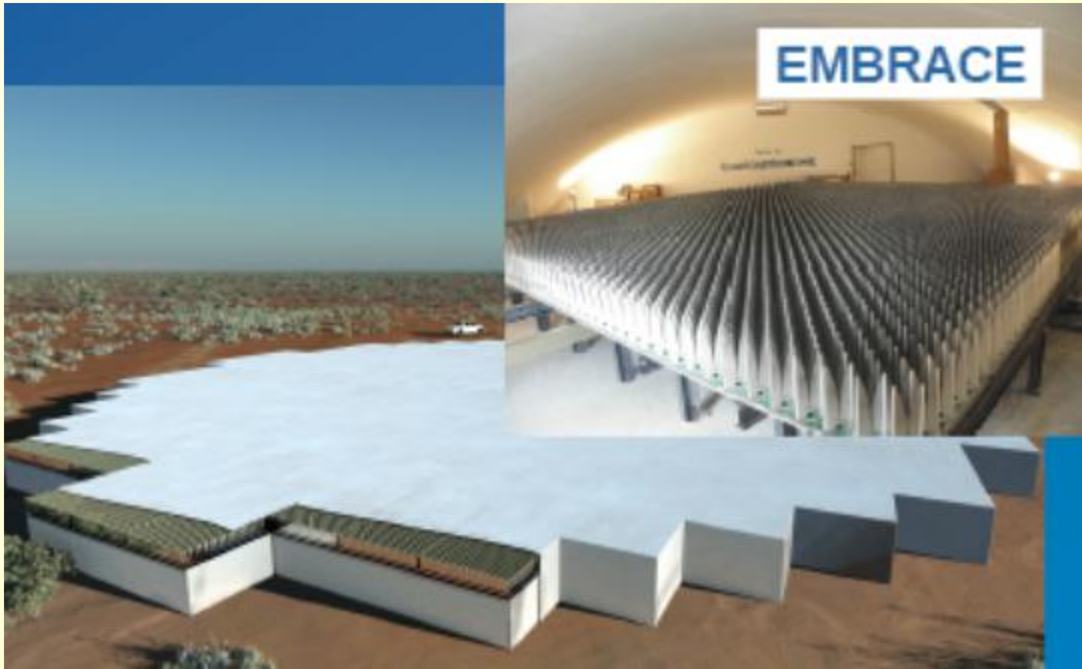
Gravitational radiation
Adaptive nulling
Big Bang
Evolving galaxies
Pulsar
First astronomical objects
SETI
Gamma-ray burster
Probing the early Universe
Adaptive nulling

New technology, new problems

LOFAR:
RFI ionospheric seeing, sidelobes of strong sources, calibrations, etc..

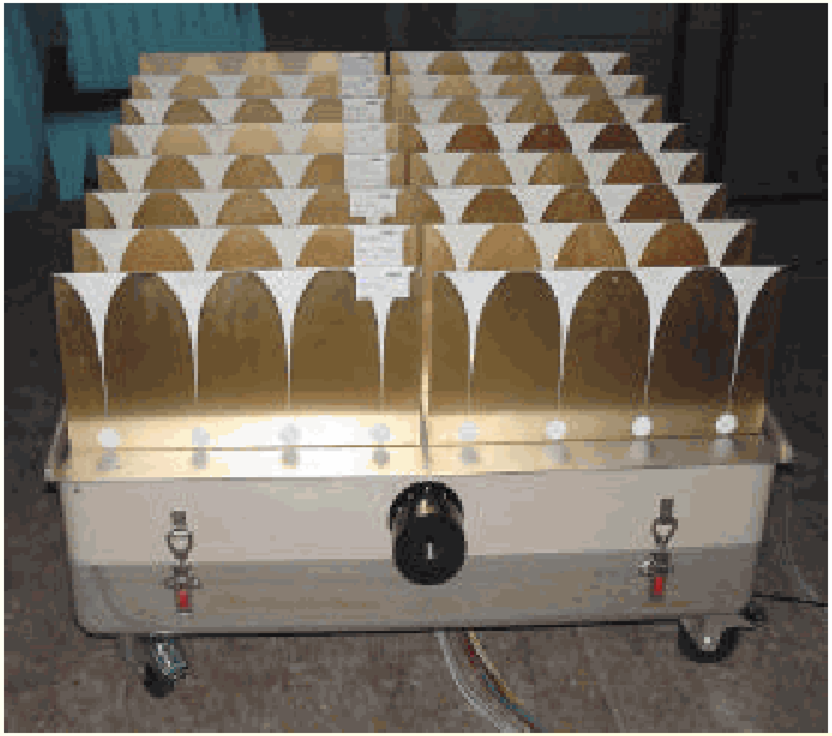
Low frequency: **EMBRACE** Beamforming

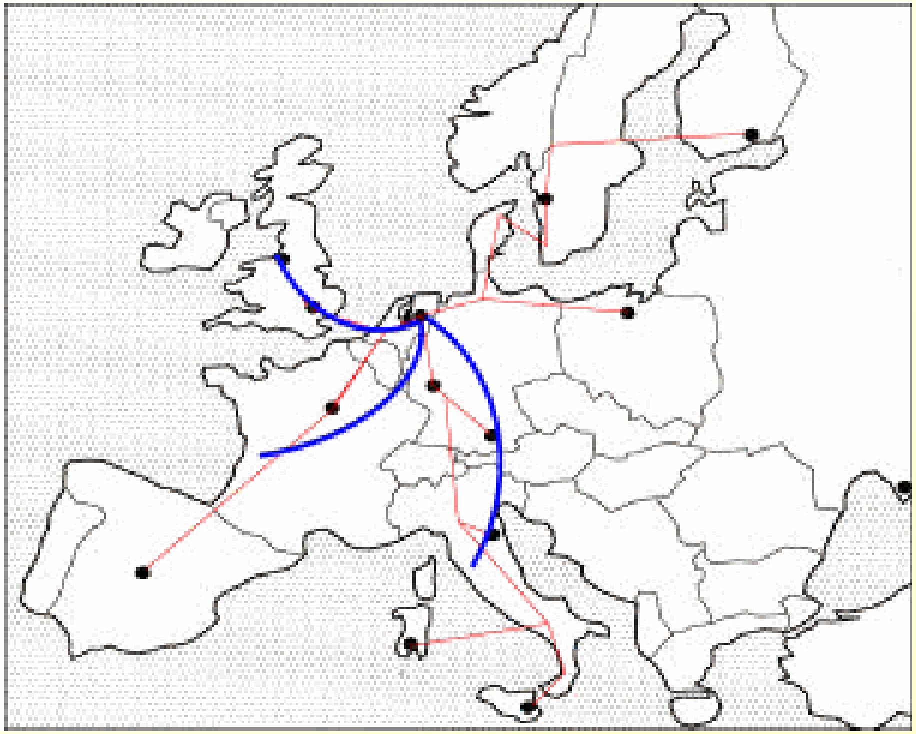




EMBRACE

Electronic MultiBeam Radio Astronomy ConcEpt





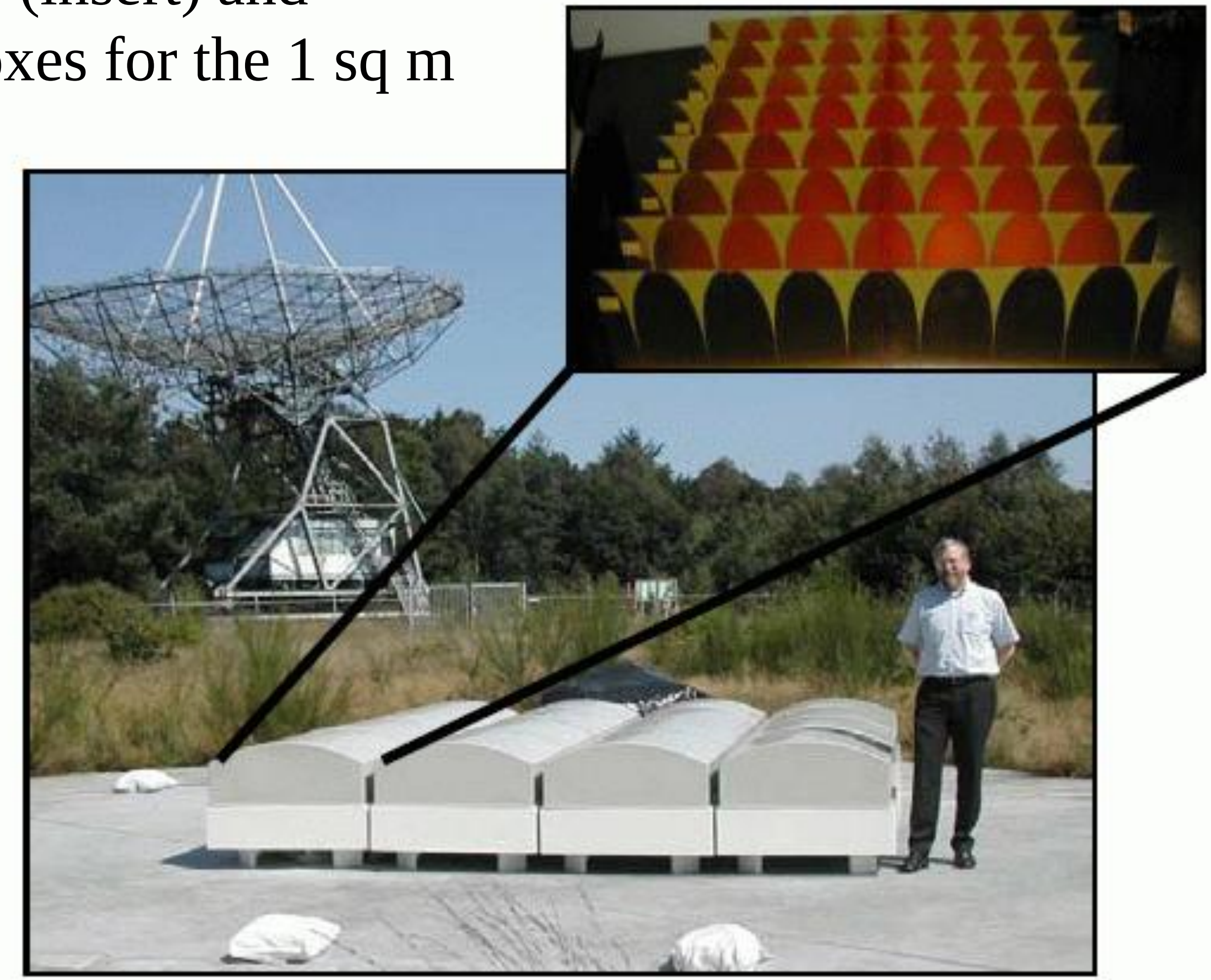
➔THEA array of 1 sq m, built at ASTRON

Beamforming system below, to form 2 fields of view

➔Schematic view of EMBRACE demonstrator (fibre network) 100 m^2

Aperture Arrays

Vivaldi array (insert) and protective boxes for the 1 sq m array of tiles



SKA: a World-wide project

55 institutes from 19 countries (10 only members)

- 150 scientists and engineers involved in the project
- at present 100+ FTE/year on R&D activities and construction

- estimated SKA construction cost : 1.5 GEUR
- acquired R&D funding over 2007-2012: 140 MEUR

Terminology:

- SKA **Precursors**: the three radio telescopes being built on the two selected SKA sites

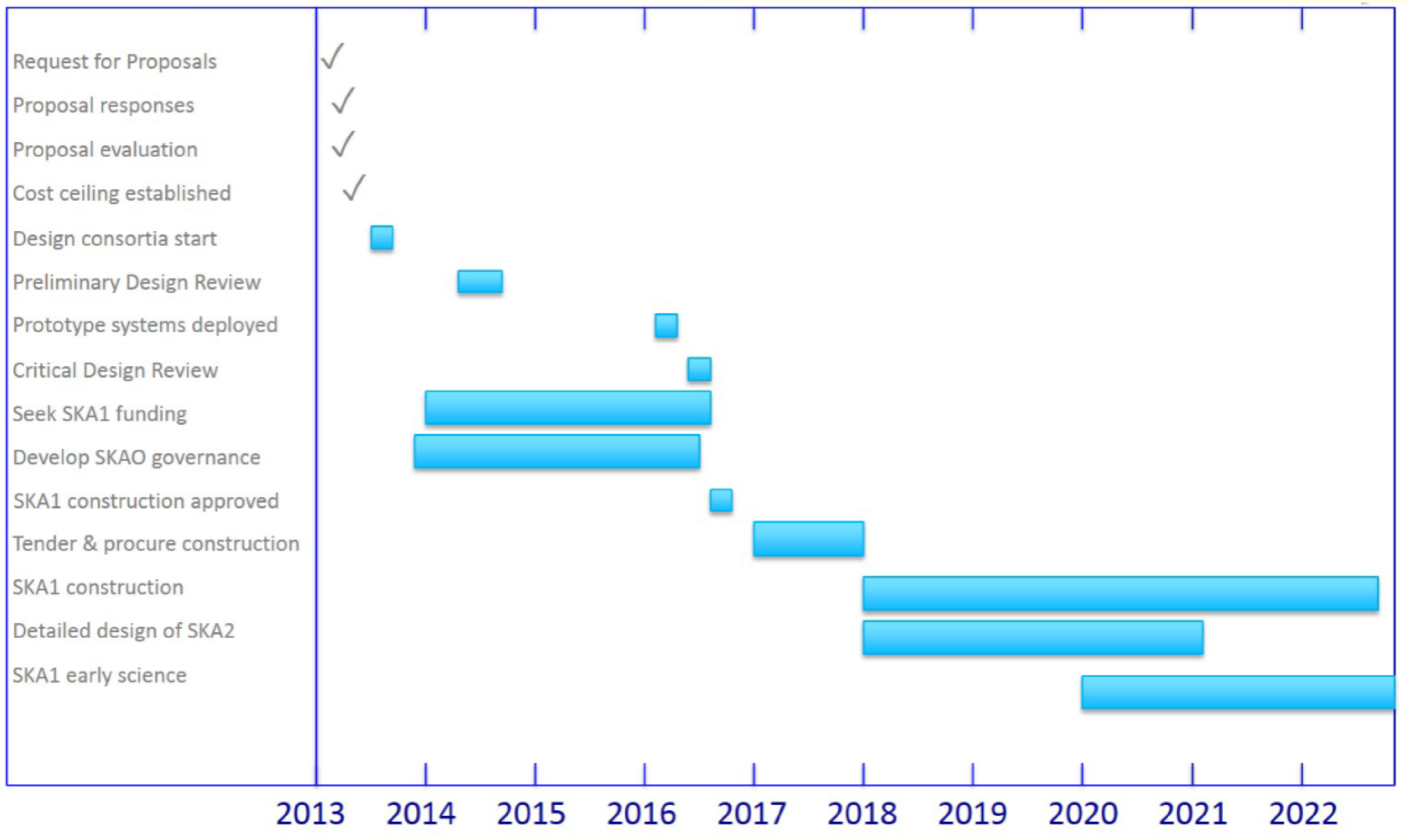
ASKAP and MWA in Australia

MeerKAT in South Africa

- SKA **Pathfinders**: facility or instrument that contributes R&D/other knowledge of direct use to the SKA **(e.g., LOFAR)**

Time-scales

- **2018 – 2021:** construction of **SKA1**
- **2019/20:** early science begins
- **2022 – 2025:** construction of **SKA2**
- **SKA** operational for 50 years.



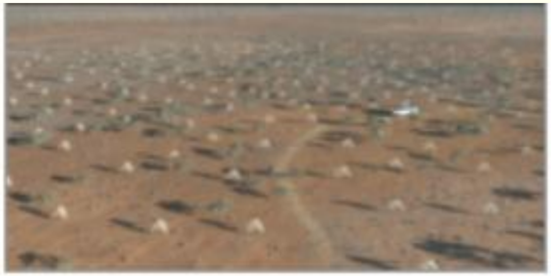
The SKA phases 1 & 2 < 2015

Africa

Australia

SKA1_MID
254 Dishes including:
64 x MeerKAT dishes
190 x SKA dishes

SKA1
400Me
2017



SKA1_LOW
50 x Low Frequency Aperture Array Stations

SKA1_SURVEY
96 Dishes including:
36 x ASKAP
60 x SKA dishes

JVLA/meerKat➔**SKA1-mid**		LOFAR➔**SKA1-low**	ASKAP➔**SKA1-surv**
Sensitivity	6 xJVLA	16xLOFAR	6xASKAP
Survey Speed	74	520	22

Africa

SKA2_MID
2500 Dishes

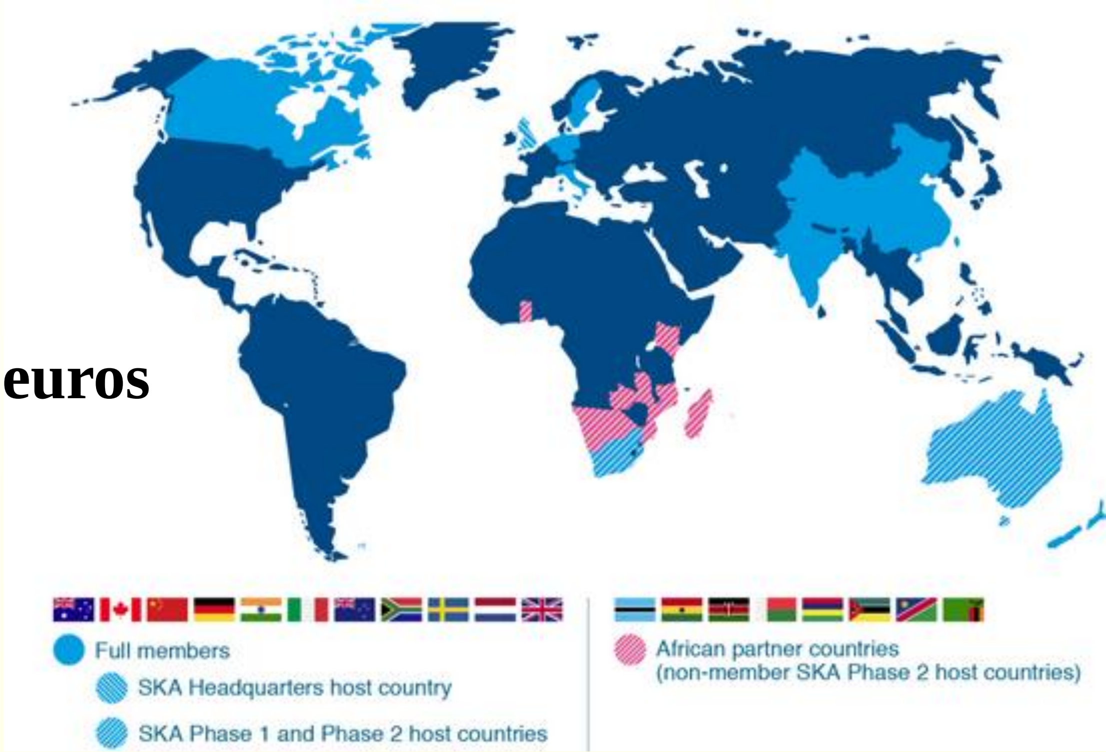
SKA2_AA
Mid Frequency Aperture Array Stations

SKA2
2022

Australia

SKA2_LOW
Low Frequency Aperture Array Stations

Rebaselining 2015



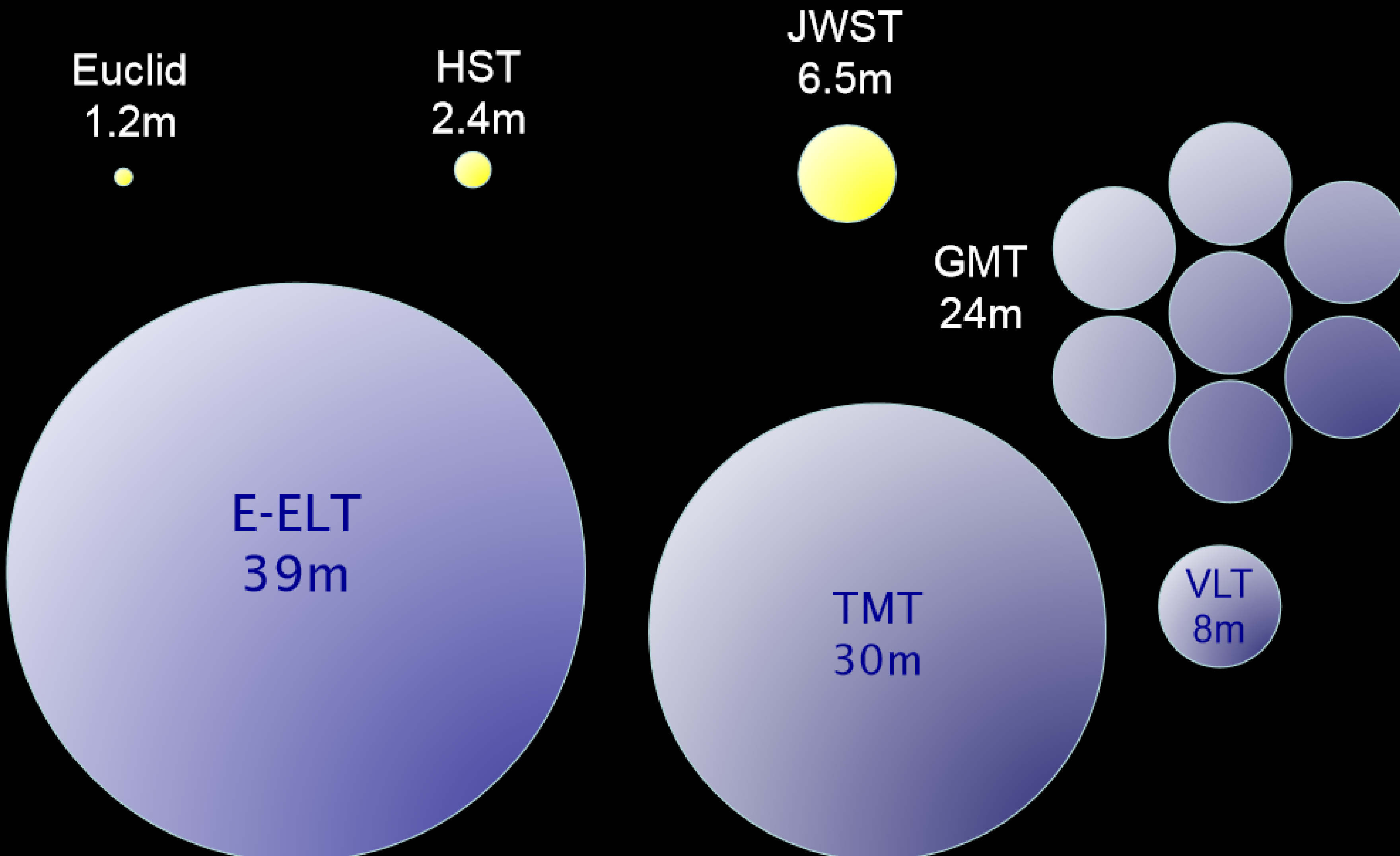
The SKA cost was **1 billion euros**

In 2014, SKA board capped at **650 Meuros**

➔Deferring the SKA1-survey
➔Reducing SKA1-mid to 70%
➔Reducing SKA1-low to 50%

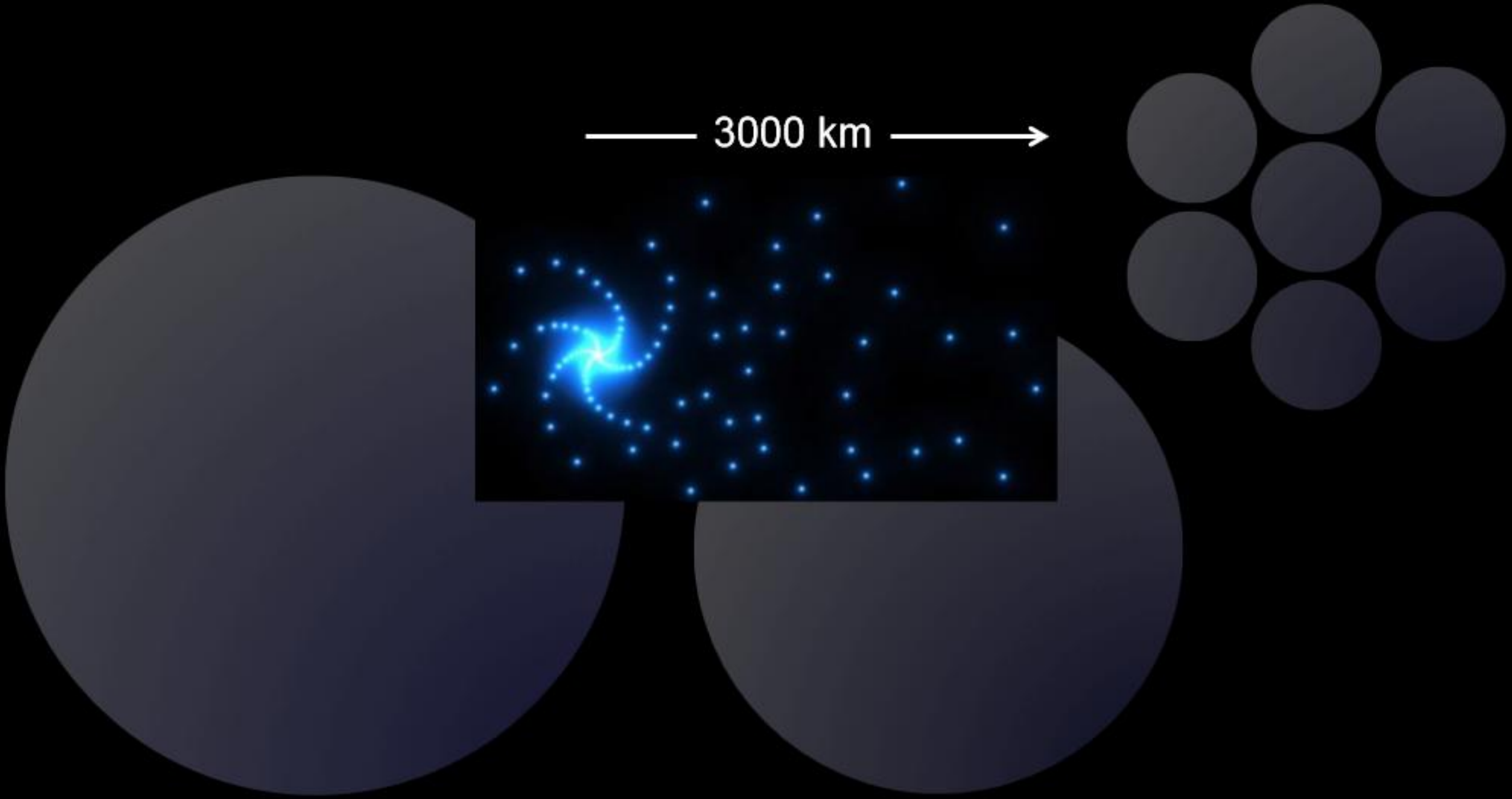
New science book: 2000 pages, 135 chapters, published in 2015
Organisations from ten countries are currently members of the SKA Organisation – Australia, Canada, China, India, Italy, New Zealand, South Africa, Sweden, the Netherlands, UK
40% of world population!

Telescope primary mirrors



Collecting area = sensitivity
Diameter = resolution
Field of view = mapping speed

SKA footprint to scale /100,000



Three SKA Precursors

ASKAP: Australia **Frequency 0.7-1.8 GHz (HI at z=1)**

36 ×12m parabolic antennas: collecting surface 4000 m2
multi-beam Phased Array Feeds: field-of-view 30 sq.degrees
instantaneous bandwidth: 300 MHz
optimised for 30 arcsec resolution

MEERKAT: South Africa **Frequency 0.7-1.8 GHz (HI at z=1)**

80 ×12m parabolic antennas: collecting surface 8000 m2
single-pixel feeds: field-of-view 1 sq.degree
instantaneous bandwidth: 1 GHz
versatile in resolution: 6-80 arcsec
Both: construction started, fully operational 2016

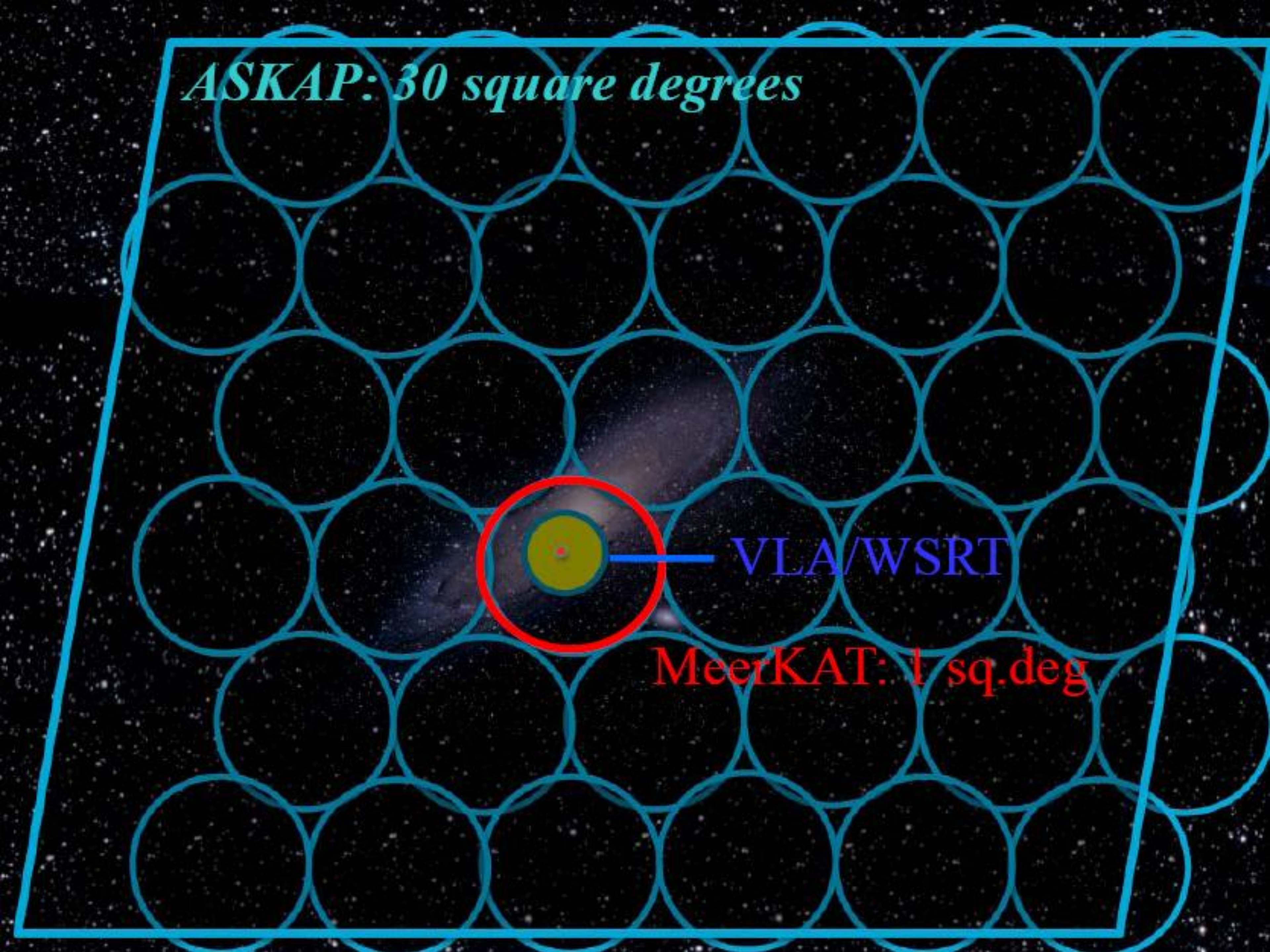
MWA: Australia **80-300MHz** 2048 dipoles in 128 tiles

Array fixed, **FoV 25°** at 150 MHz Resolution a few arcmin (1.5km)

ASKAP

MeerKAT

SKA AFRICA
SQUARE KILOMETRE ARRAY


ASKAP: 30 square degrees
VLA/WSRT
MeerKAT: 1 sq.deg

SKA precursor Complementarity with pathfinders

ASKAP:
-large fields/all-sky, relatively shallow surveys

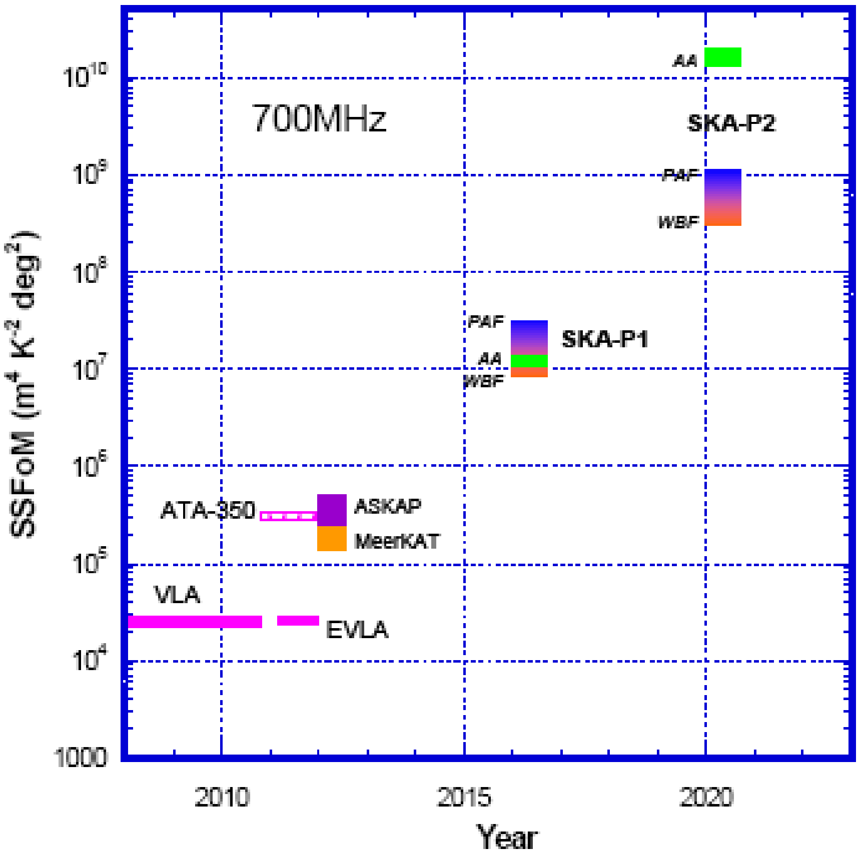
MeerKAT
-smaller fields, deeper surveys, higher/lower resolution

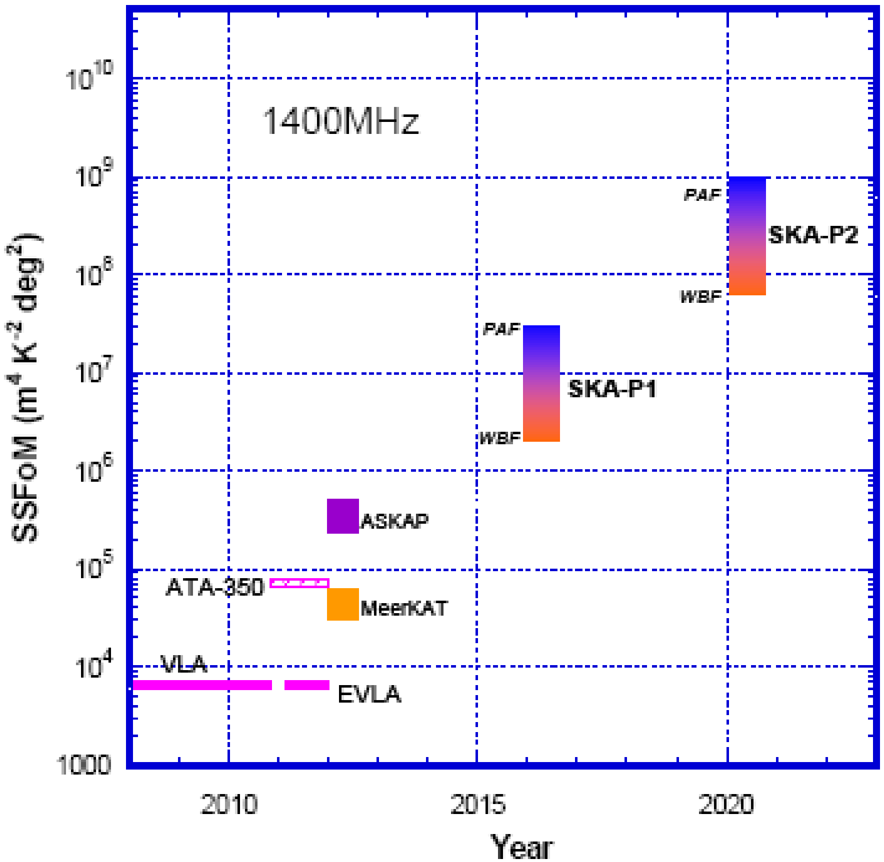
WSRT + APERTIF:
-northern hemisphere, overlap in δ+25°-30°strip only

VLA:
-deep integration of small fields, down to δ-40 °only

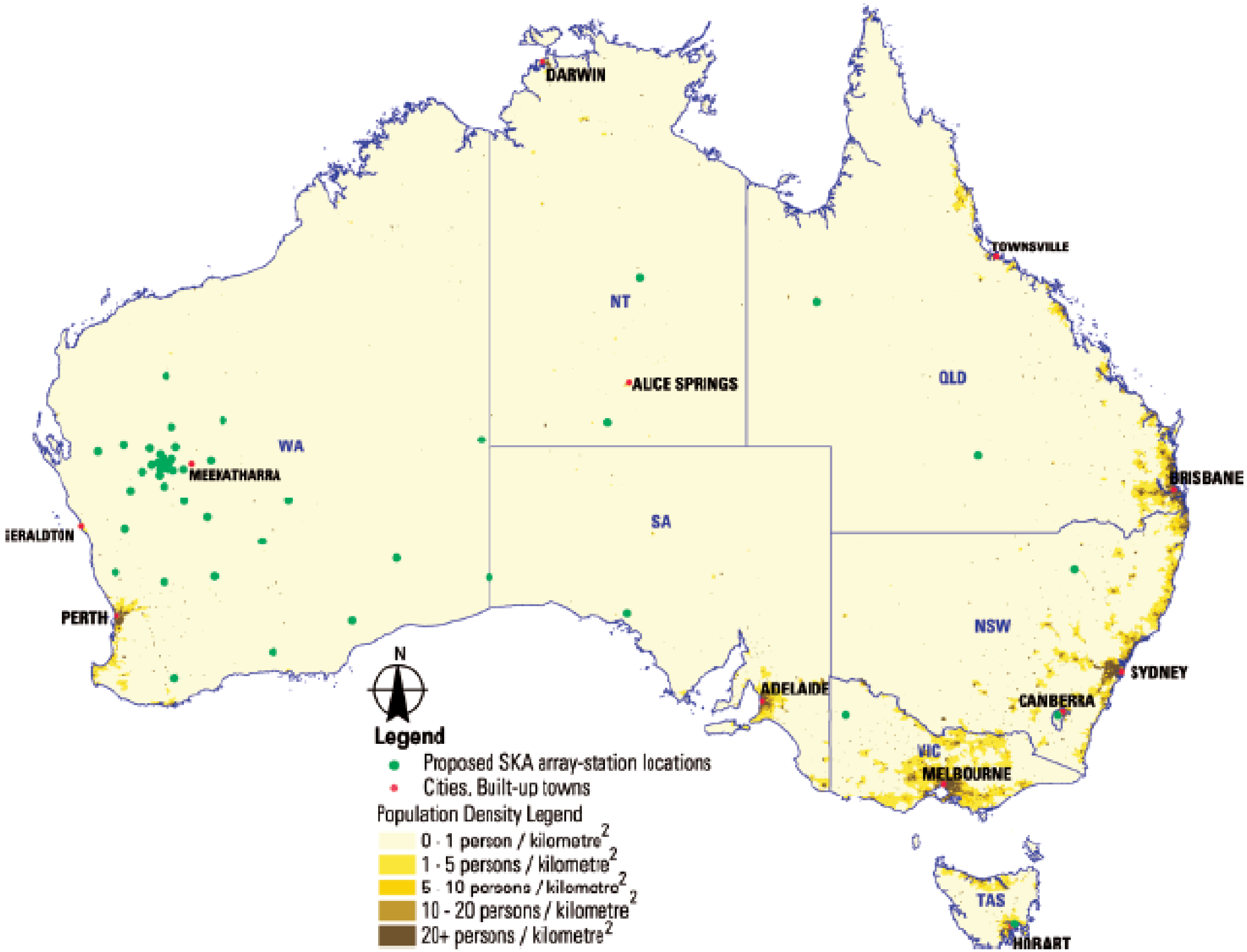
NENUFAR (Nancay) the lowest frequency!

SKA survey speeds

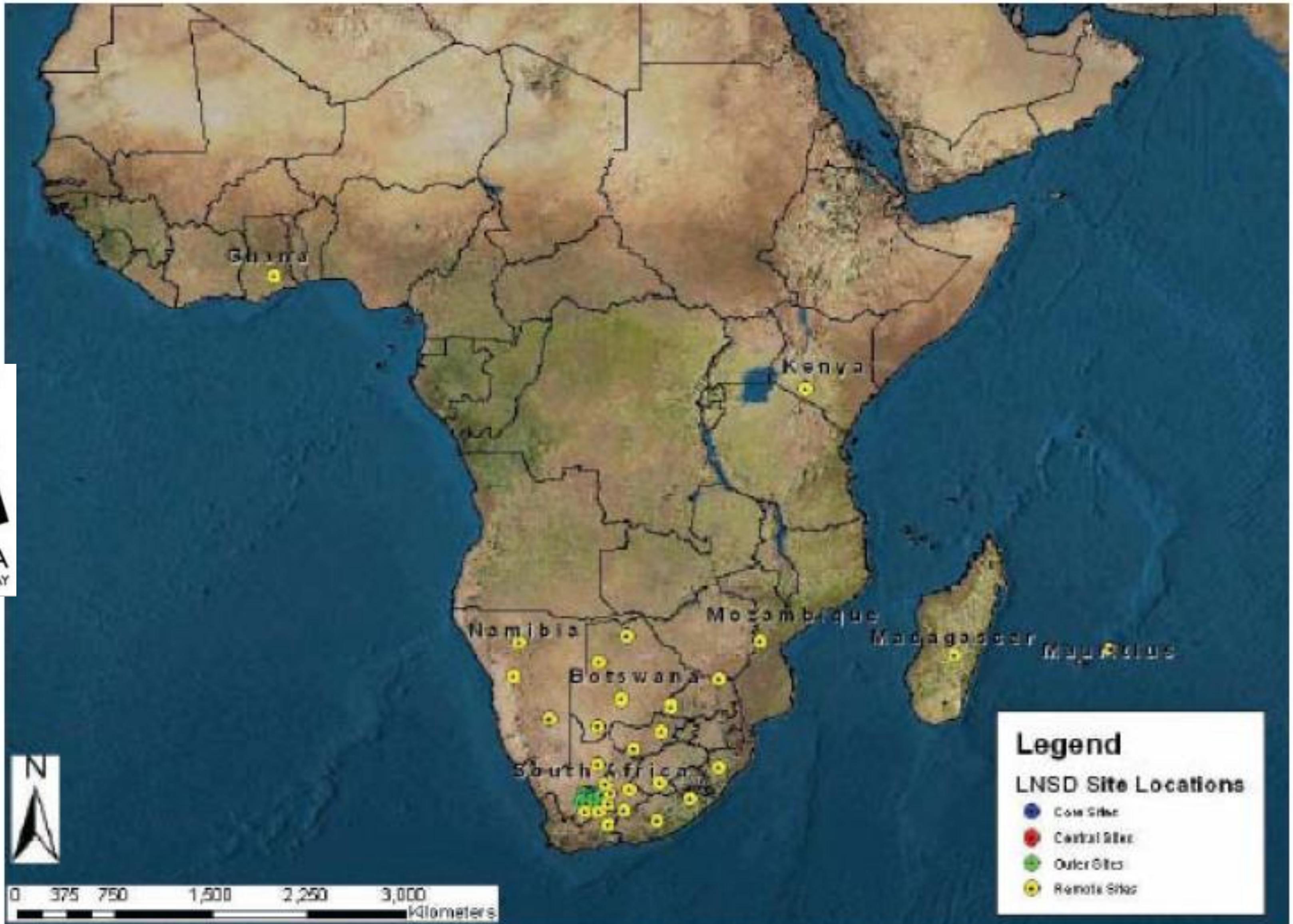


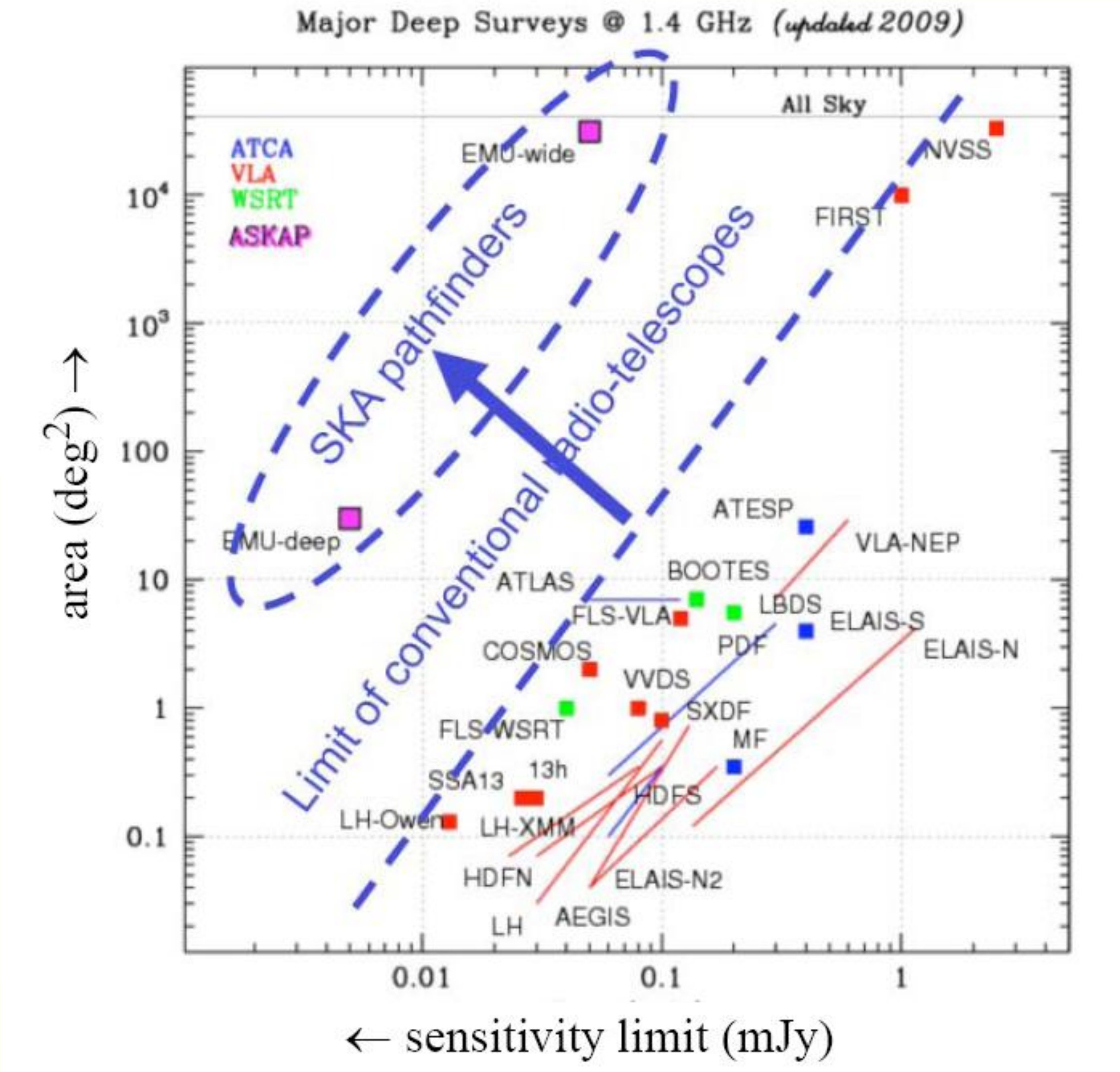


Australia


DARWIN
NT
ALICE SPRINGS
TOWNSVILLE
QLD
BRISBANE
WA
MEEKATHARRA
ERALDTON
PERTH
SA
NSW
SYDNEY
CANBERRA
ADELAIDE
VIC
MELBOURNE
TAS
HOBART
N
Legend
Proposed SKA array-station locations
Cities, Built-up towns
Population Density Legend
0 - 1 person / kilometre²
1 - 5 persons / kilometre²
5 - 10 persons / kilometre²
10 - 20 persons / kilometre²
20+ persons / kilometre²

South Africa + 7 countries




Major Deep Surveys @ 1.4 GHz (updated 2009)
All Sky
ATCA
VLA
WSRT
ASKAP
EMU-wide
NVSS
FIRST
SKA pathfinders
Limit of conventional radio-telescopes
EMU-deep
ATESP
VLA-NEP
ATLAS
BOOTES
FLS-VLA
LBDS
ELAIS-S
PDF
ELAIS-N
COSMOS
VVDS
SXDF
FLS-WSRT
MF
SSA13
13h
HDFS
LH-Owen
LH-XMM
HDFN
ELAIS-N2
LH
AEGIS
0.01
0.1
1
0.1
1
10
100
10^3
10^4
area (deg^2) →
← sensitivity limit (mJy)

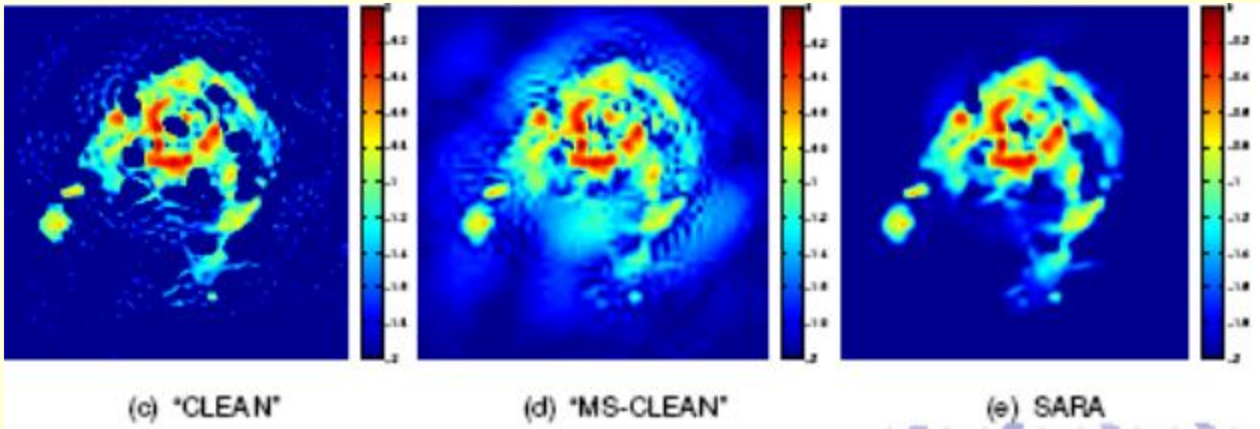
Data management

A huge challenge, for SKA: Petabytes/sec
Petaflops machines working continuously (~10^8 PC)
Exabytes per hour, dishes=**10x global internet,**
Phased arrays =100x global internet traffic!

LSST: more than half of the cost!
Machine learning software

Euclid: 100Gbytes /day

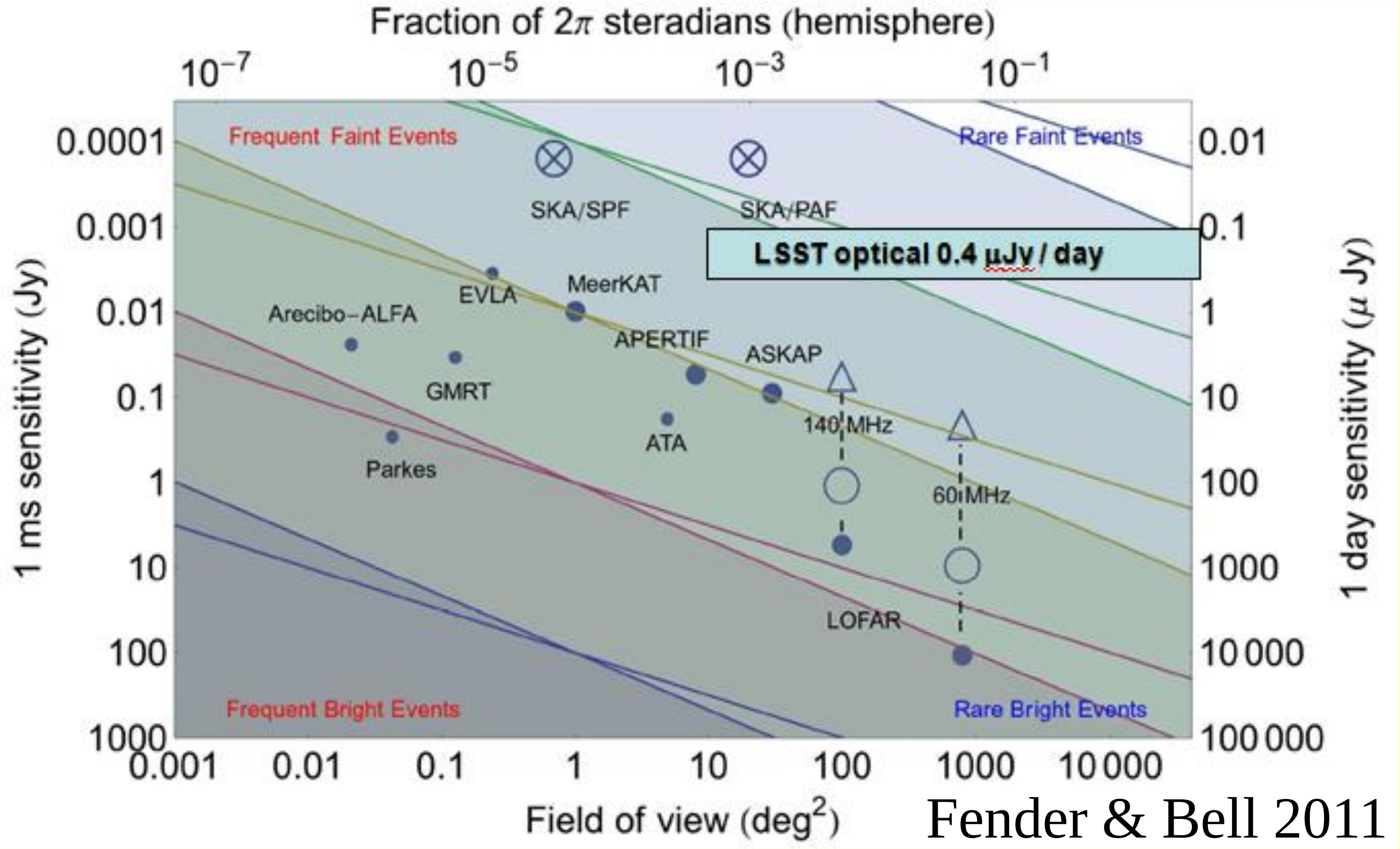
Sparsity,
Compressive sensing
Jason McEwen



A new dimension: the transient sky

4 FRB found , 5 FRB per day expected with SKA2

LSST (Large Synoptic Telescope) millions of alerts/day



Fender & Bell 2011

PopIII SN?

Dishes

High frequency SKA1
(South Africa)

SKA1-mid +133 x 15m

Mid Frequency
SKA2
(2500 ant ~1km^2)

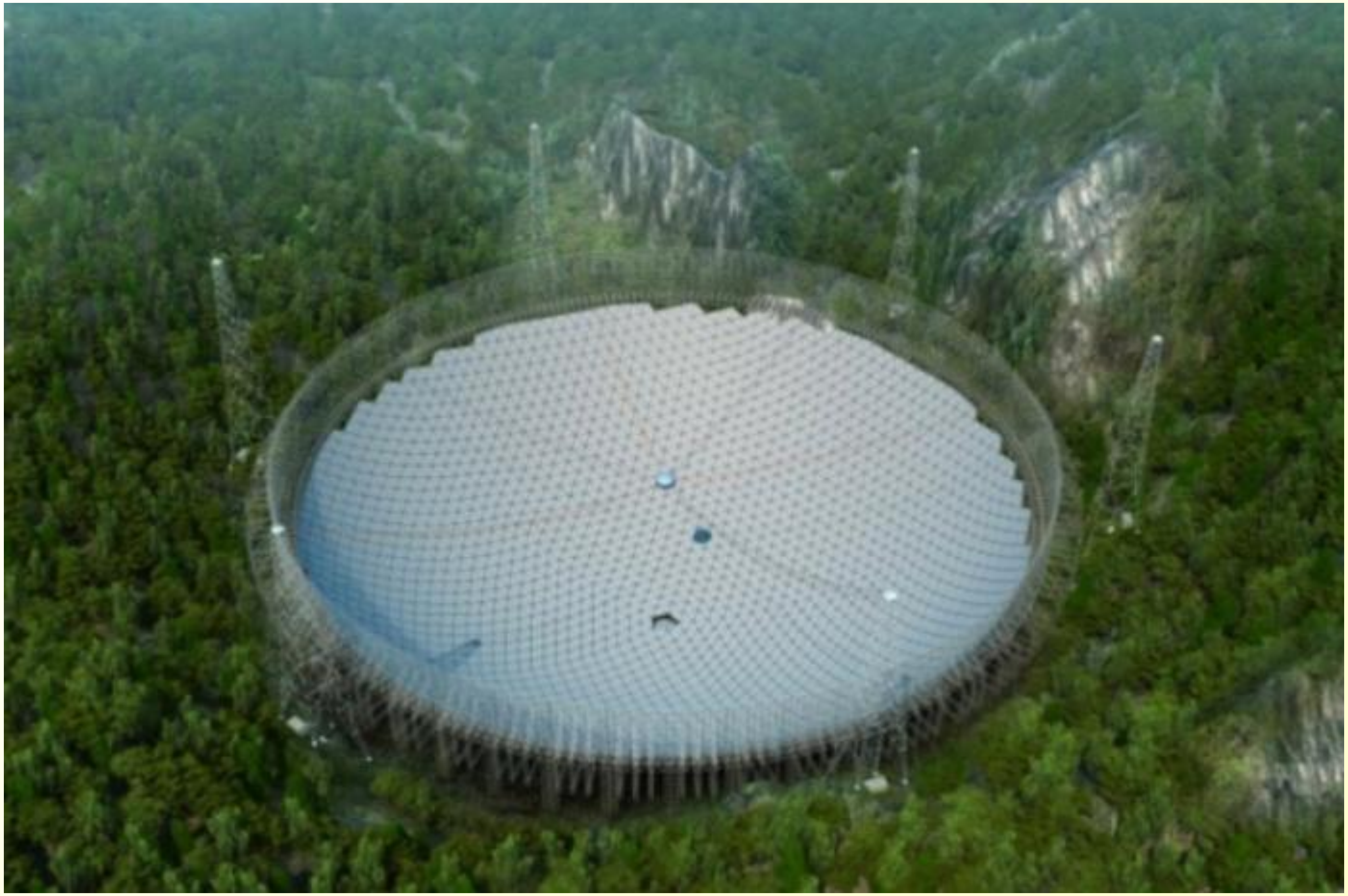
Low Frequency (Australia)

more than **900 stations**, each containing a bit less than **300 individual dipole antennas**, as well as a **96-dish** 'SKA1-Survey' telescope, incorporating the existing 36-dish ASKAP

www.skatelescope.org

FAST: Five hundred-m Aperture Spherical Telescope

China: Karst depression valley, in the Guizhou province.



Fixed telescope,
type Arecibo
(300m)

Surface 1/4km^2

FAST: ready in 2016?

4600 triangular panels, 3 times more sensitive than Arecibo
Adaptive optics, could observe until 40° of zenith
Frequency 0.3 and 3 Ghz, Resolution 4”

Photo: July 2015