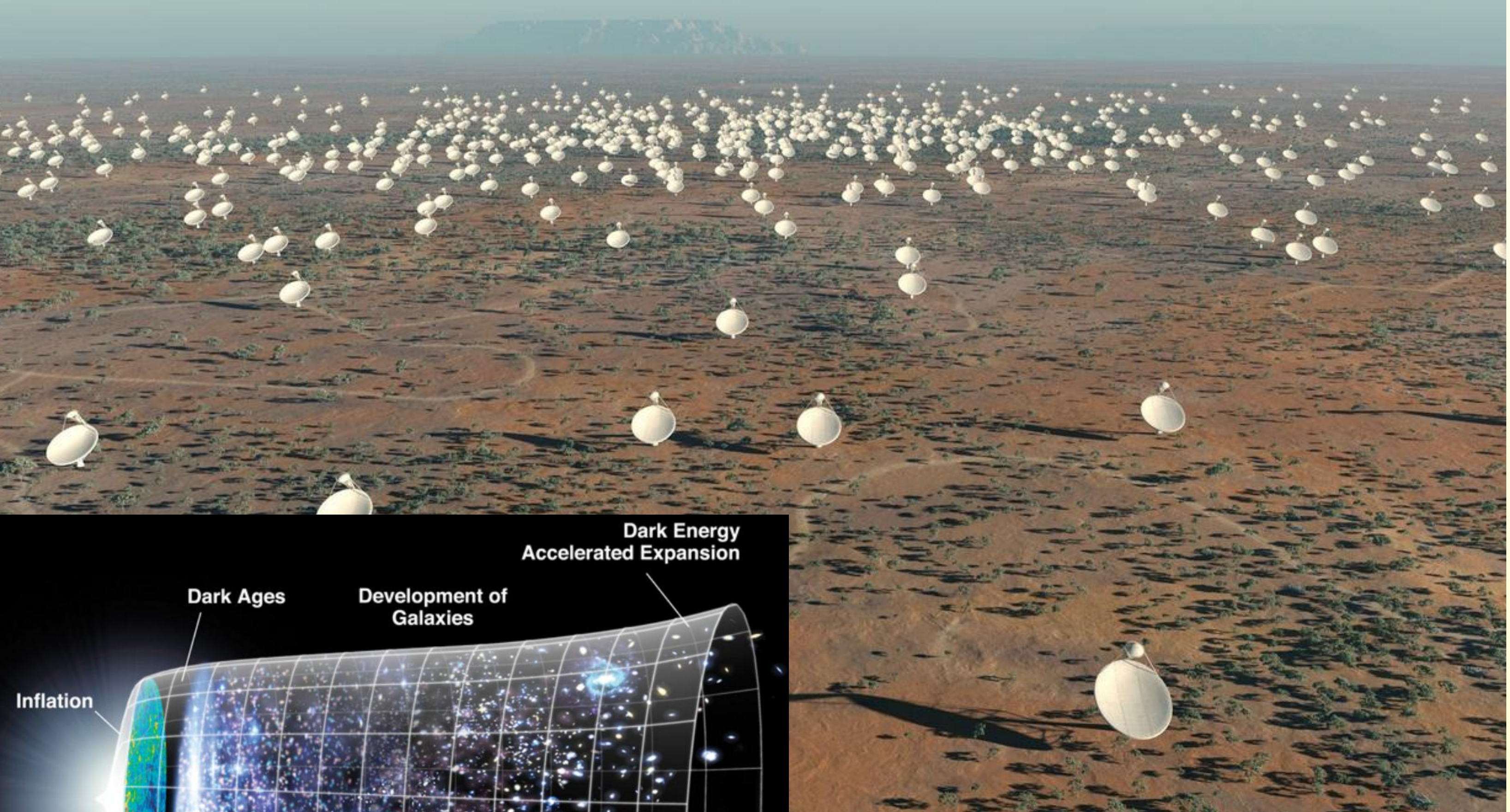
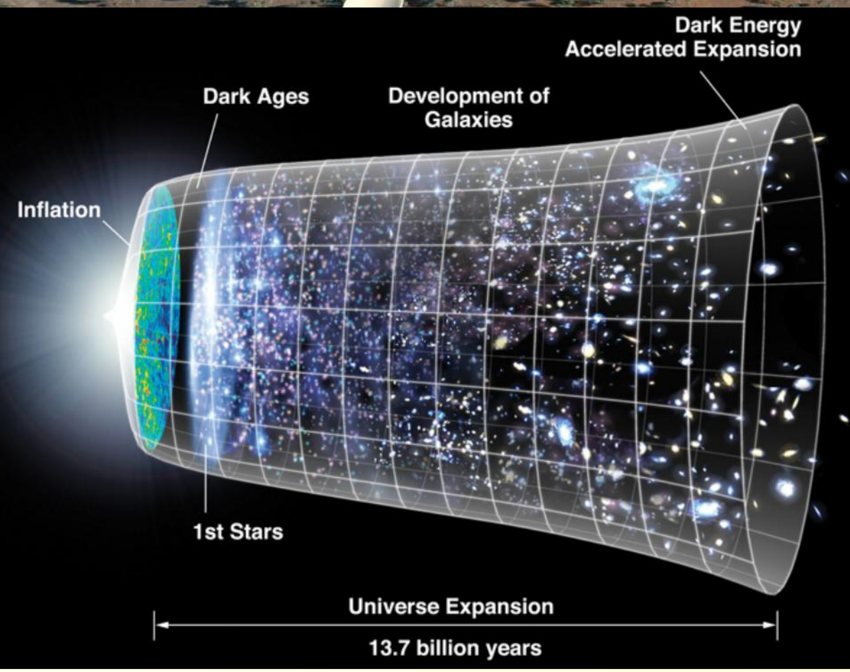




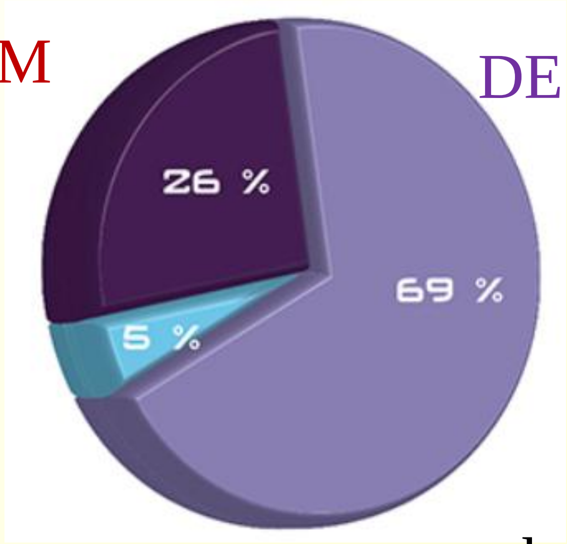
Cosmology with SKA Square Kilometer Array

Françoise Combes
Observatoire de Paris

15 July 2014

Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique

Main questions in cosmology



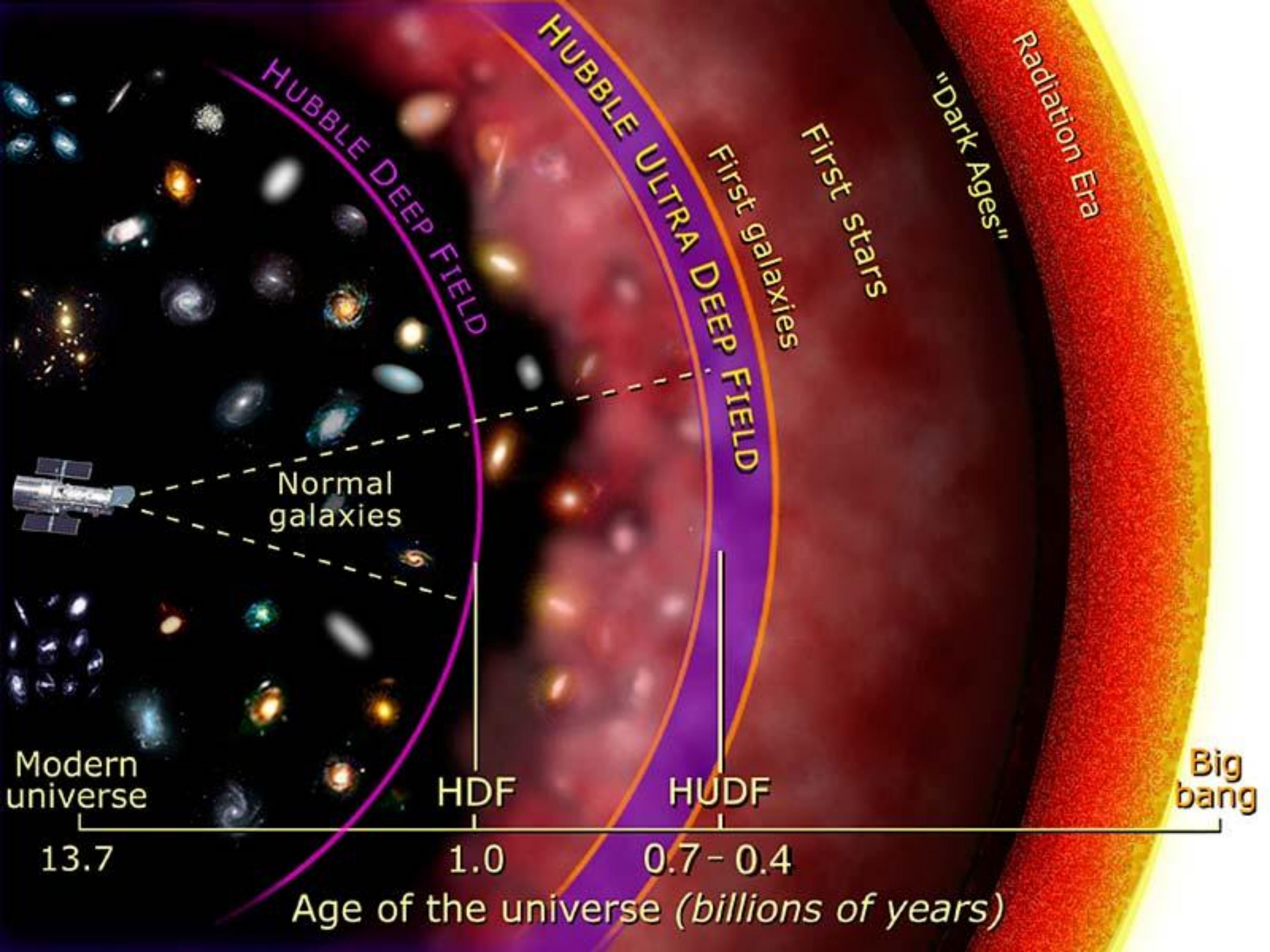
Matter in the Universe
Dark matter/visible matter vs z

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)

Big-Bang

Recombination $3\ 10^5$yr

Dark Age

1st stars, QSO $0.5 10^9$yr

Cosmic Renaissance

End of dark age

End of reionization 10^9yr

Evolution of Galaxies

Solar System $9\ 10^9$yr

Today $13.7\ 10^9$yr

First galaxies:

How do they form?

Reionization of Universe

What are the main sources

Galaxies or quasars

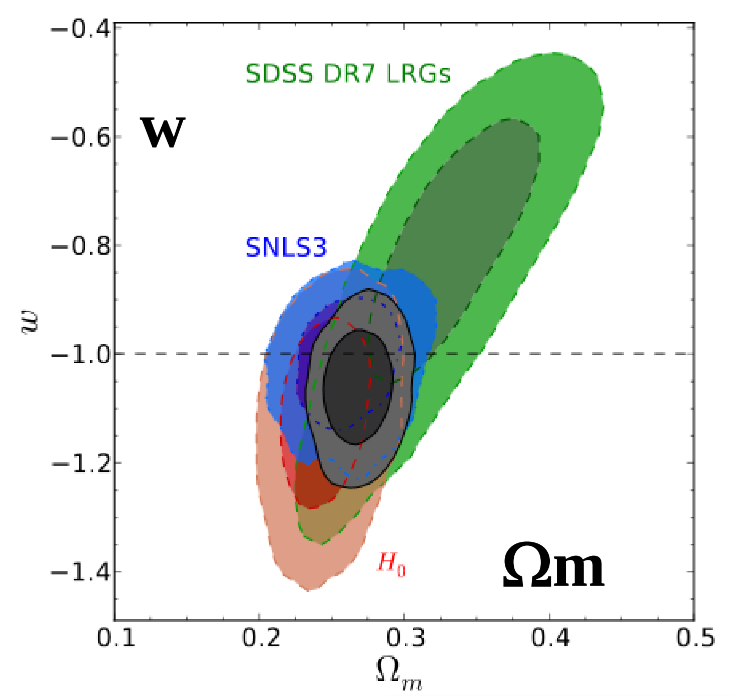
(stars or black holes)

Fate of the universe:

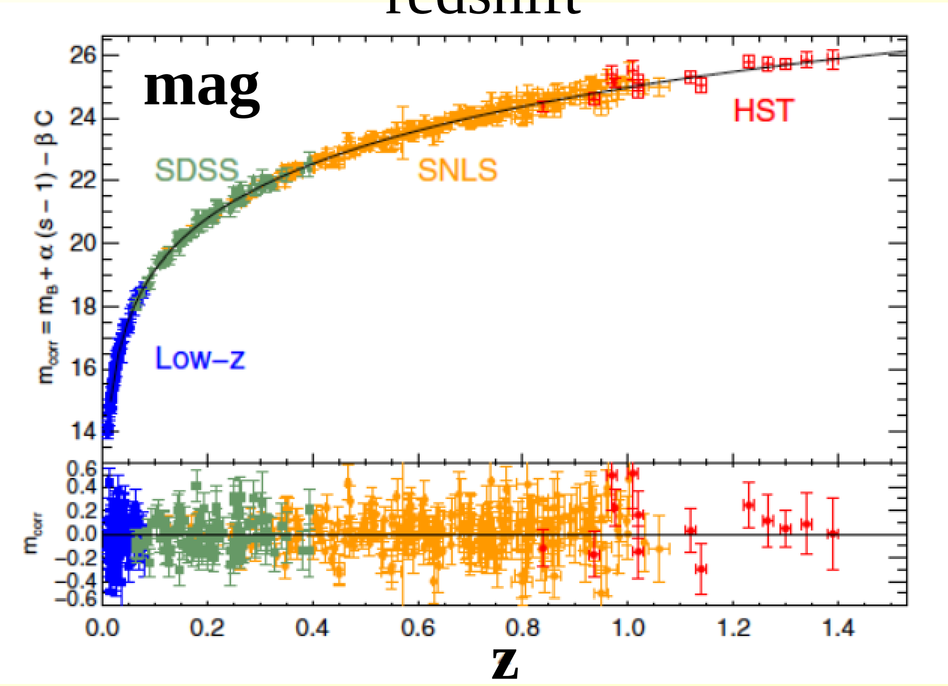
Exponential expansion?

Accelerating universe from SNIa

2003-2008 SNLS survey, French-Canadian collaboration



redshift



Sullivan et al 2011
Assuming flat universe

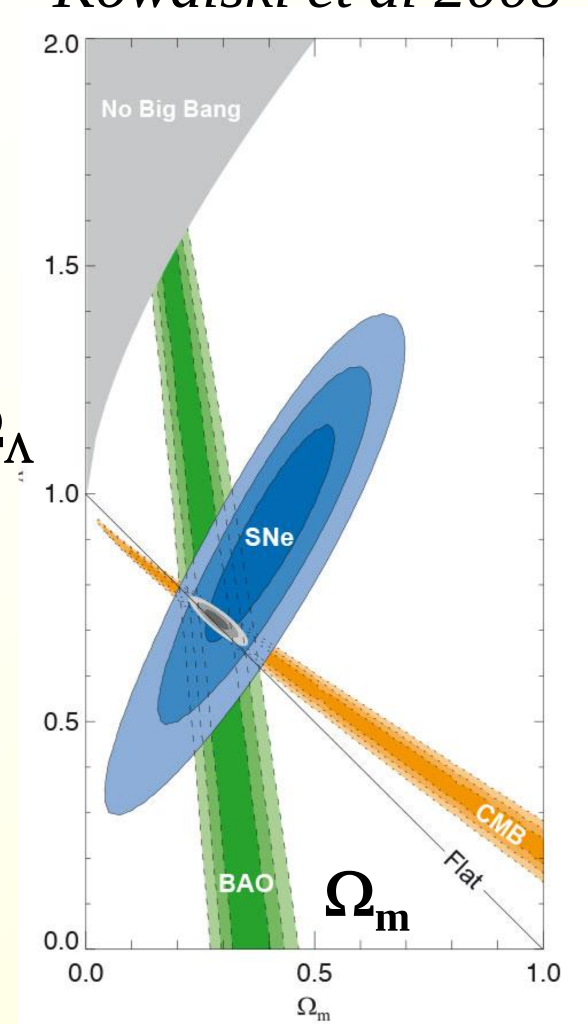
Conley et al 2011

Cosmology, Dark energy

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

Kowalski et al 2008

Ω_Λ

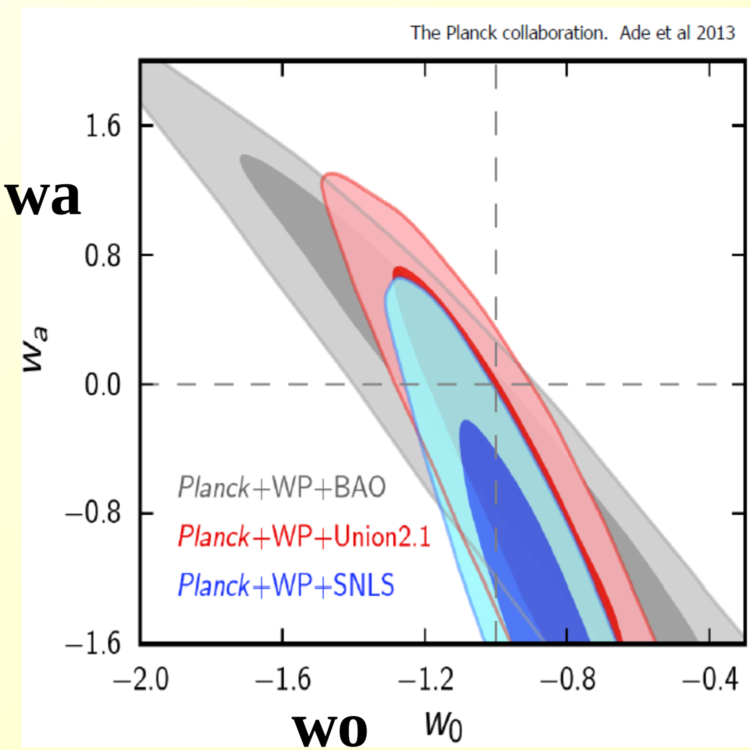


$P = w\,\rho$ $w(a) = w0 + wa\,(1-a)$

wo~-1

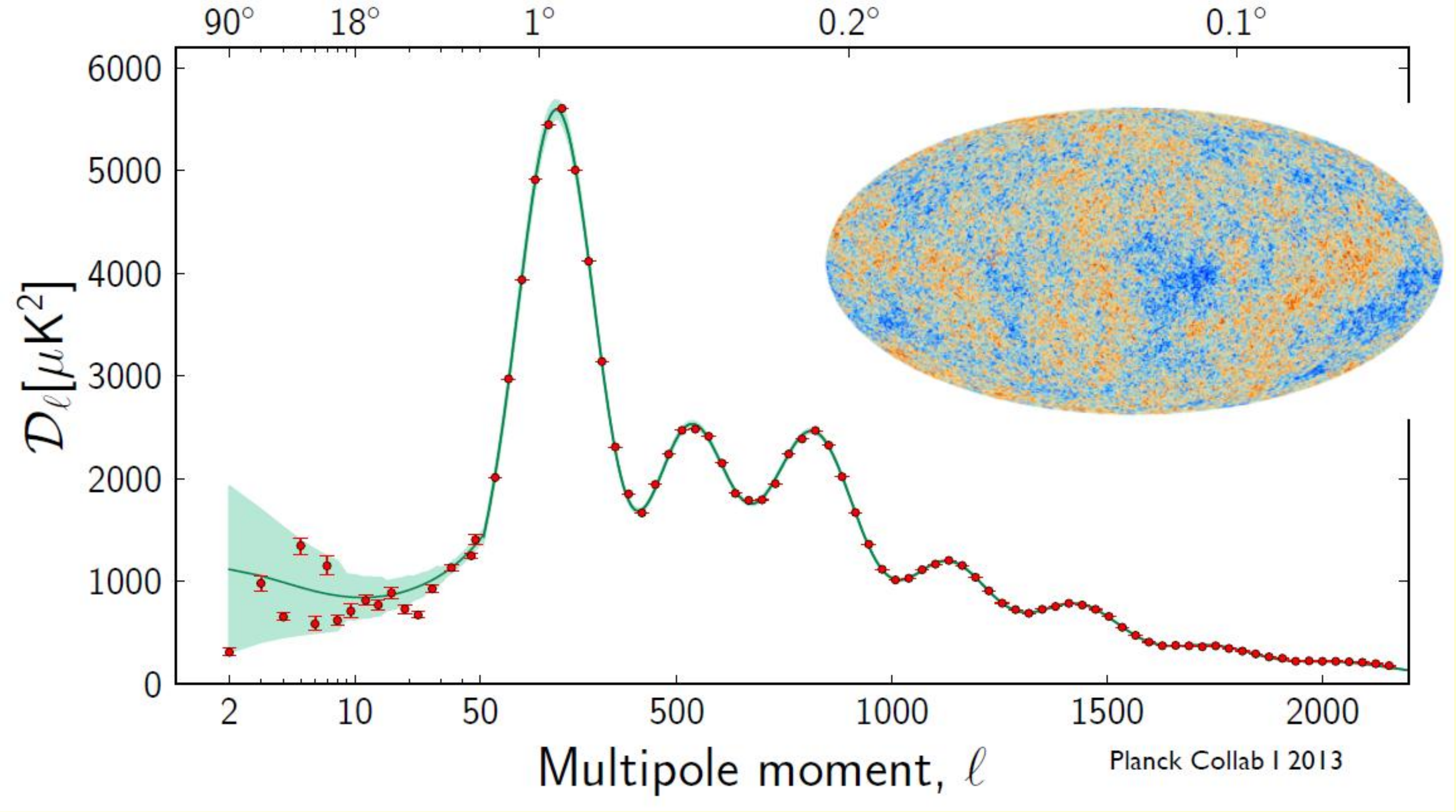
wa~0

wa



Anisotropies of the CMB

Planck Large Scales -- Not enough power at low-*l*

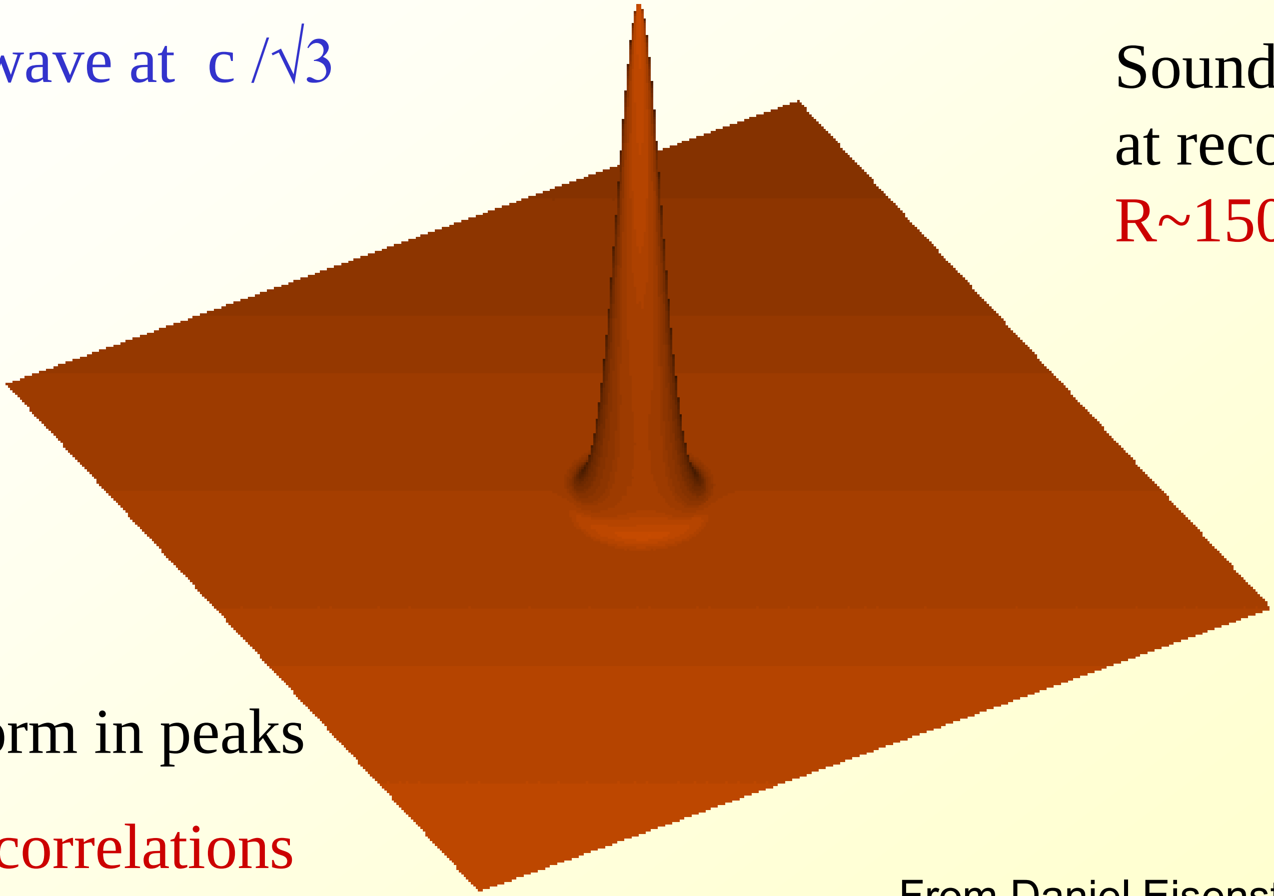


Ωb, Ωc, Peak position➔ flatness - Amplitude σ8 (at 8Mpc/ h)

A single perturbation

Creates a depression

➔ Sound wave at c /√3



Sound horizon
at recombination
R~150Mpc

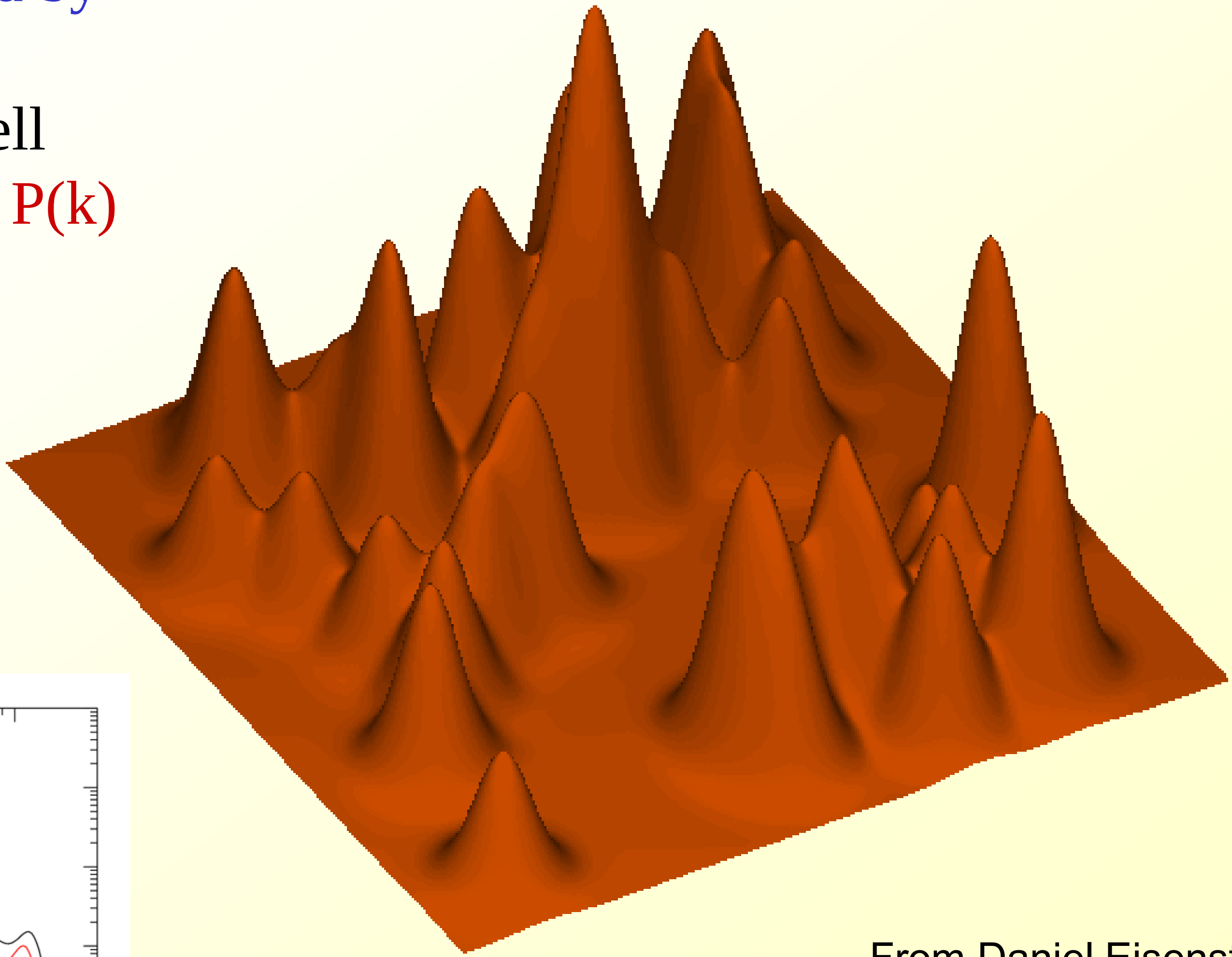
Galaxies form in peaks

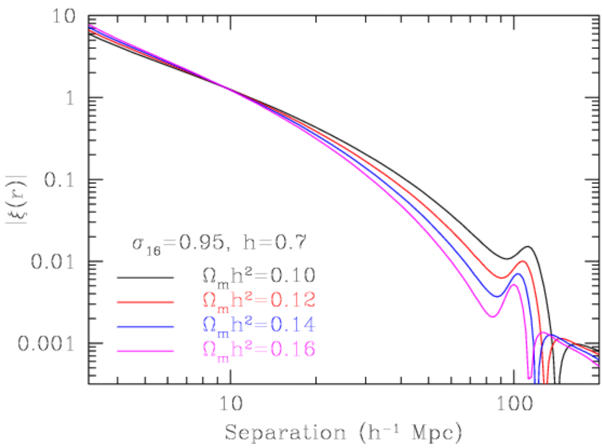
➔ baryon correlations

From Daniel Eisenstein

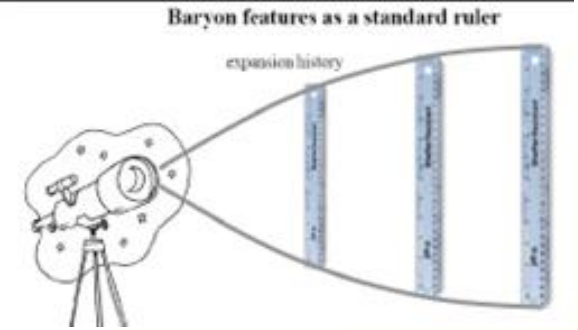
Random perturbations

- Signal reduced by random phases
- No unique shell
- But 1% in the P(k)





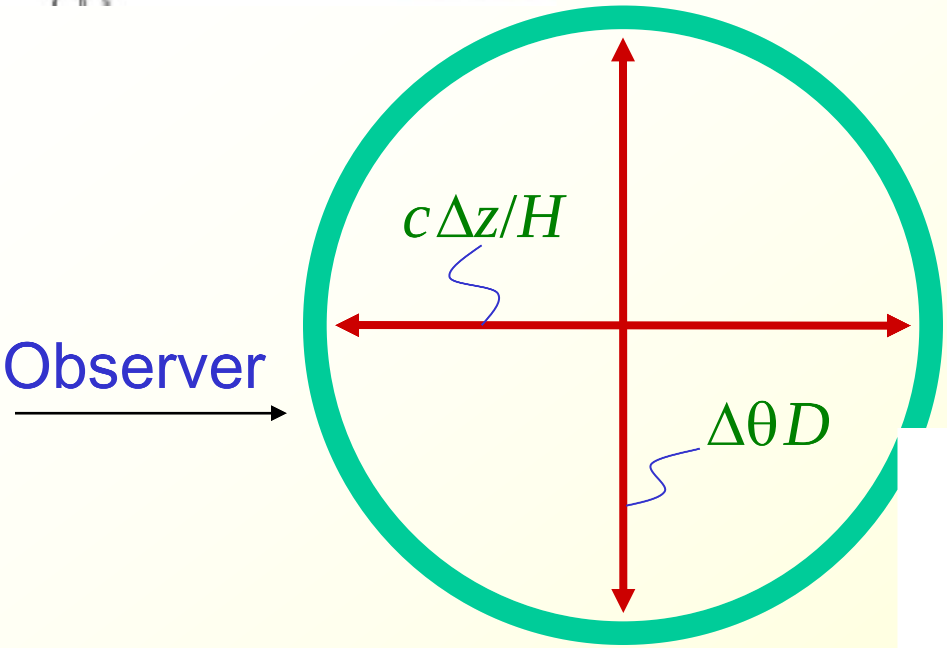
From Daniel Eisenstein



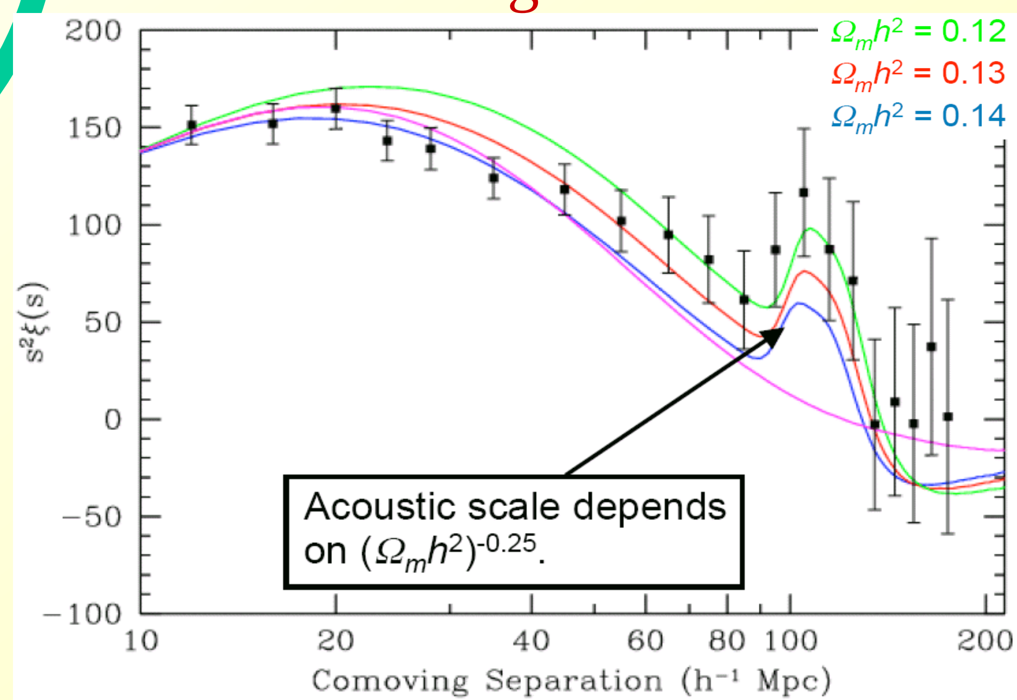
BAO: Standard Ruler

Alcock & Paczynski (1979)
Test of cosmological cst

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



Eisenstein et al. (2005)
50 000 galaxies SDSS



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

➔ Possibility to determine H(z)

HI surveys for BAO with SKA-1

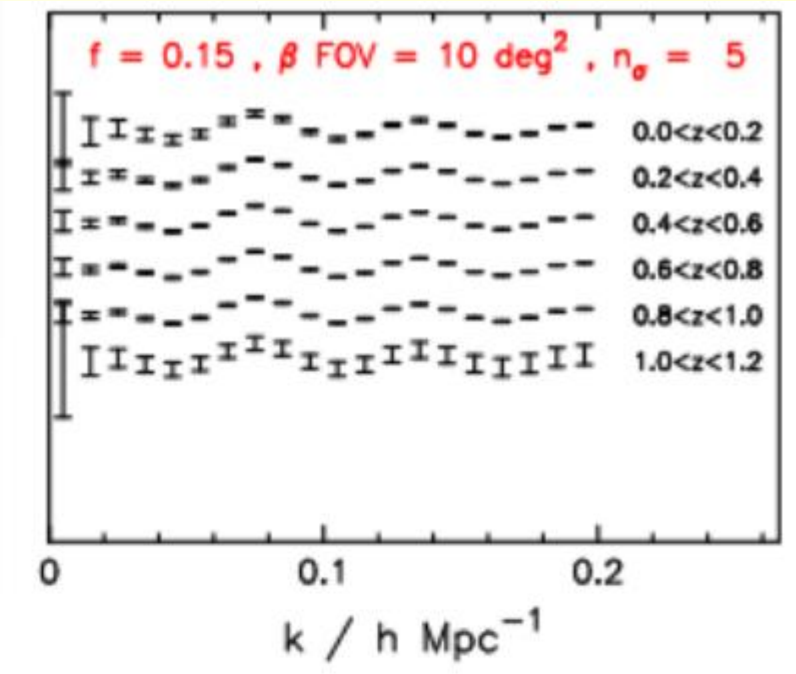
All sky survey: 4 10^6 gal z=0.2 3π sr

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

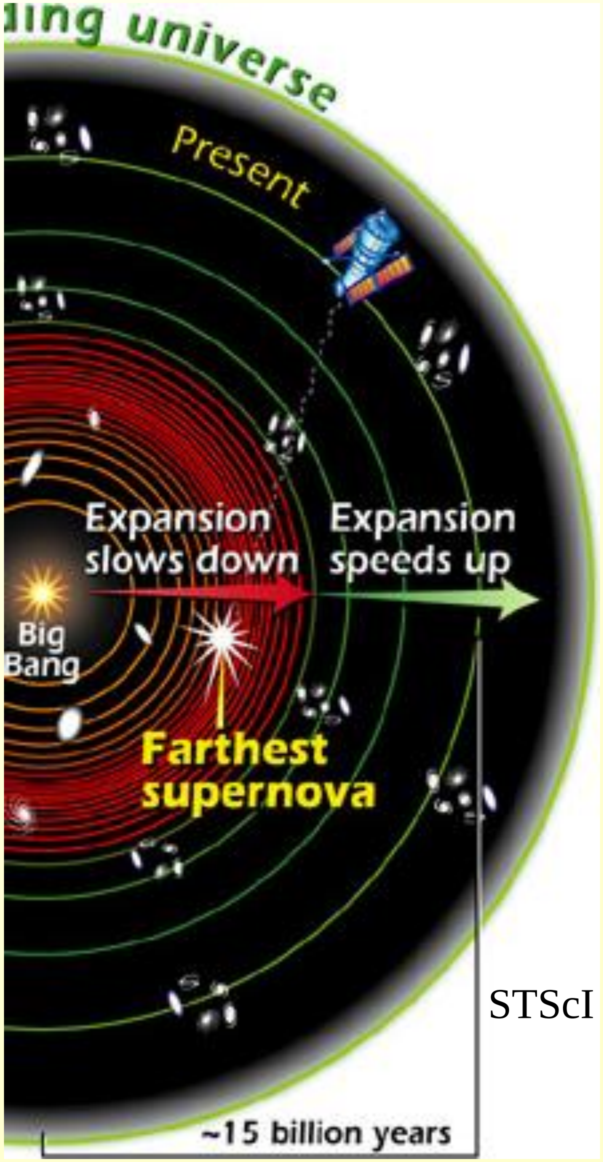
SKA will help to provide pure sample
1 billion HI galaxies in total

Weak shear
10 billions galaxies in continuum



Mapping Our History

The subtle slowing down and speeding up of the expansion, of distances with time: a(t), maps out cosmic history like tree rings map out the Earth's climate history.



STScI

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

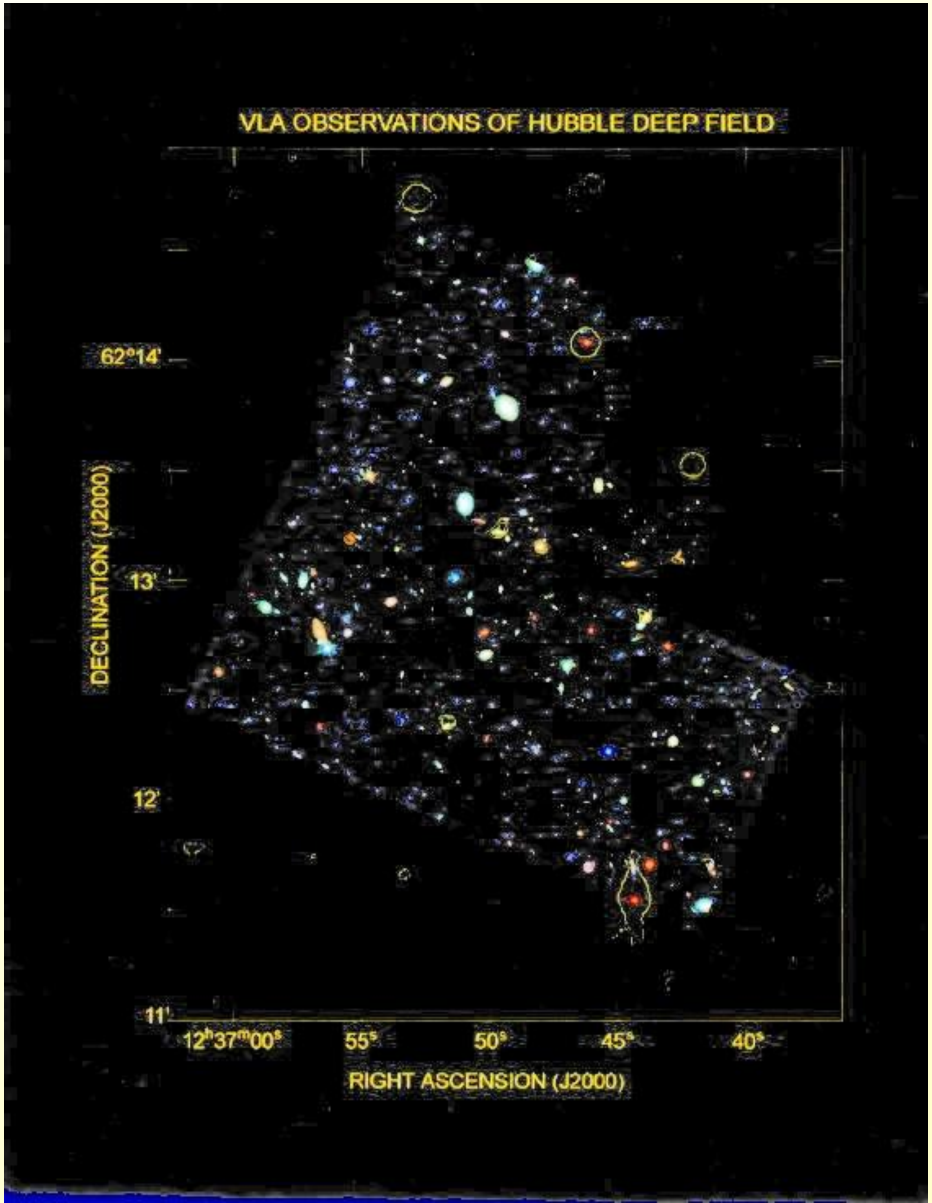
For wide-field (5000 deg2) **2 μJy rms** ≈6 galaxies $arcmin^2$ (>10σ)
For deep-field (50deg2) **0.1 μJy rms**, ≈20 galaxies $arcmin^2$ (>10σ)

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 $S_{8.4} > 12\ \mu Jy$ (50 hour observation)



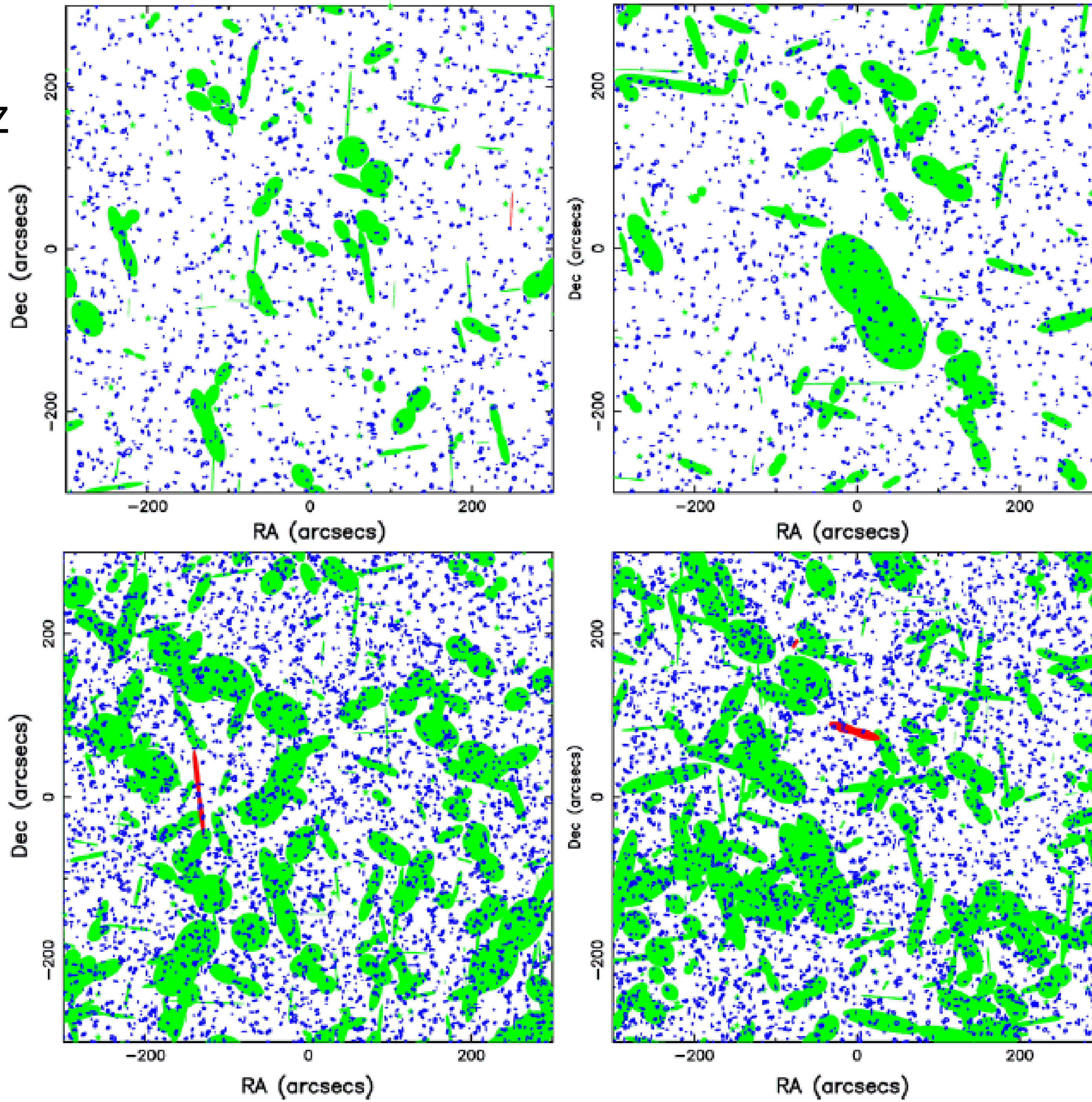
Deep radio sky
10' size, @ 1.4GHz

1mJy top
100nJy bottom
Left and Right
Cosmic variance

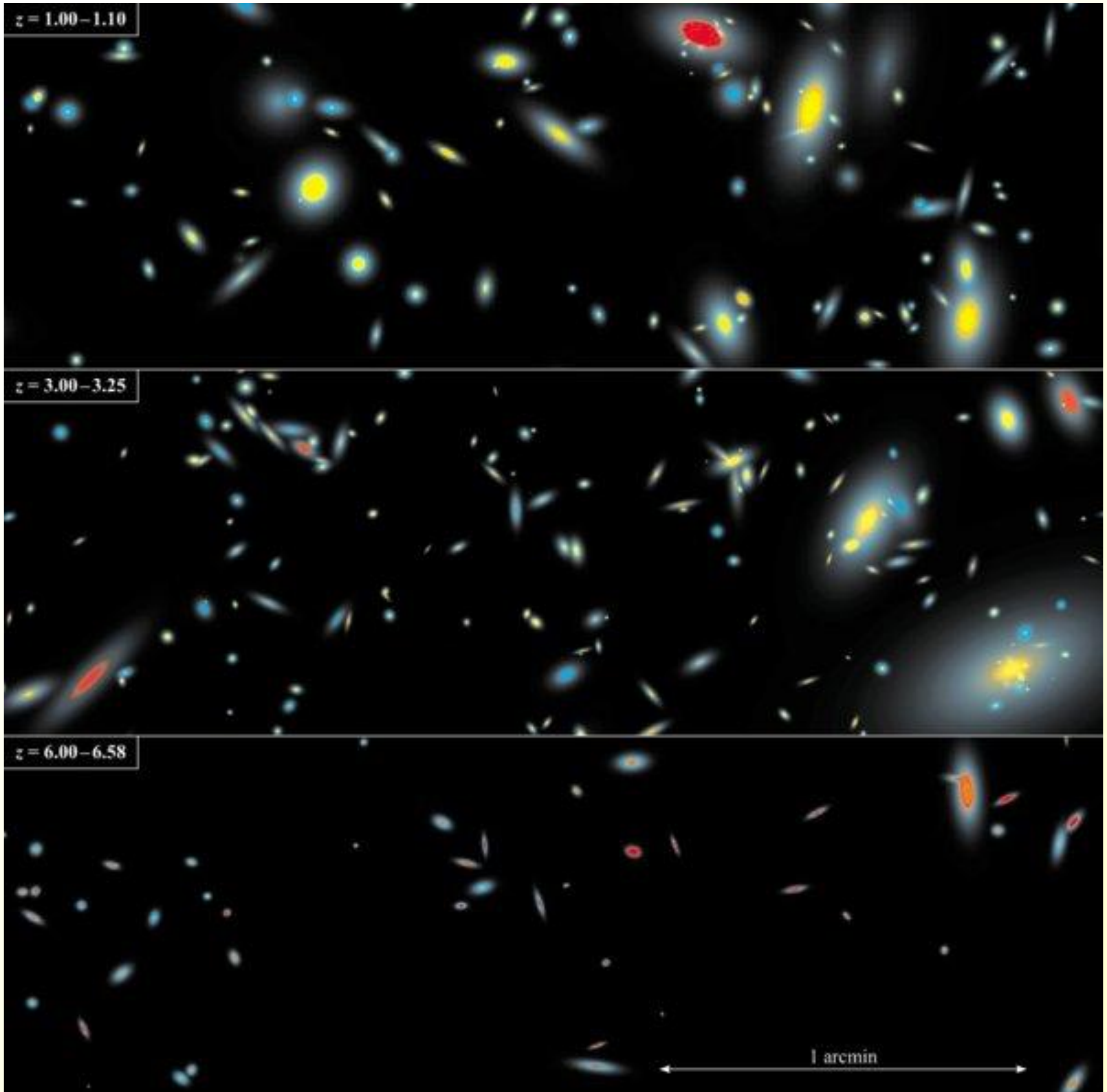
FRI: green, double
FRII: red, double

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

Jackson 2004



Simulated sky, z=1, 3, 6



Obreschkow et al 09

z=3 scale x10
z=6 scale x100

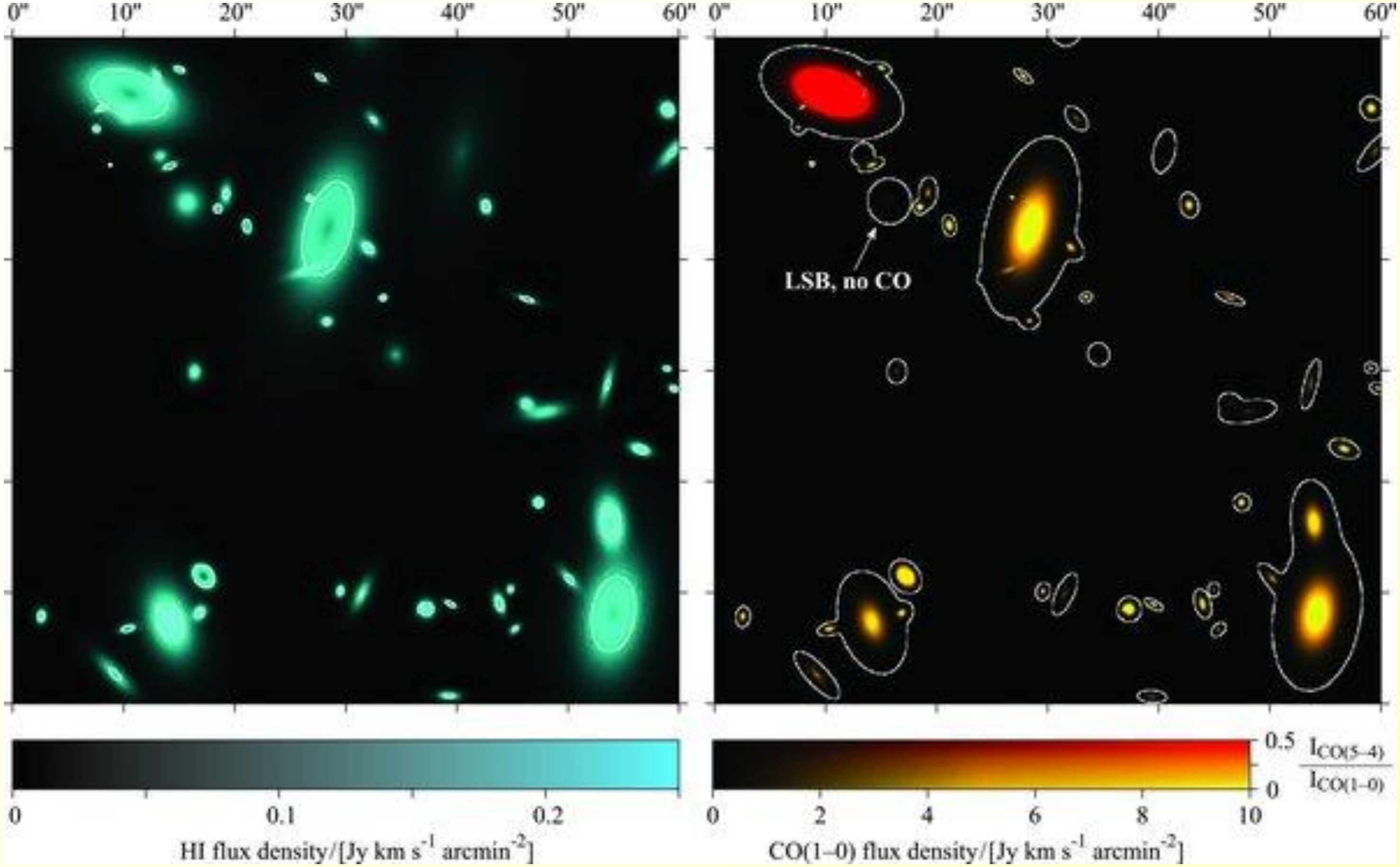
240 Mpc comoving depth
3 x 1 arcmin surface

HI line, and CO lines

Simulating the extragalactic sky

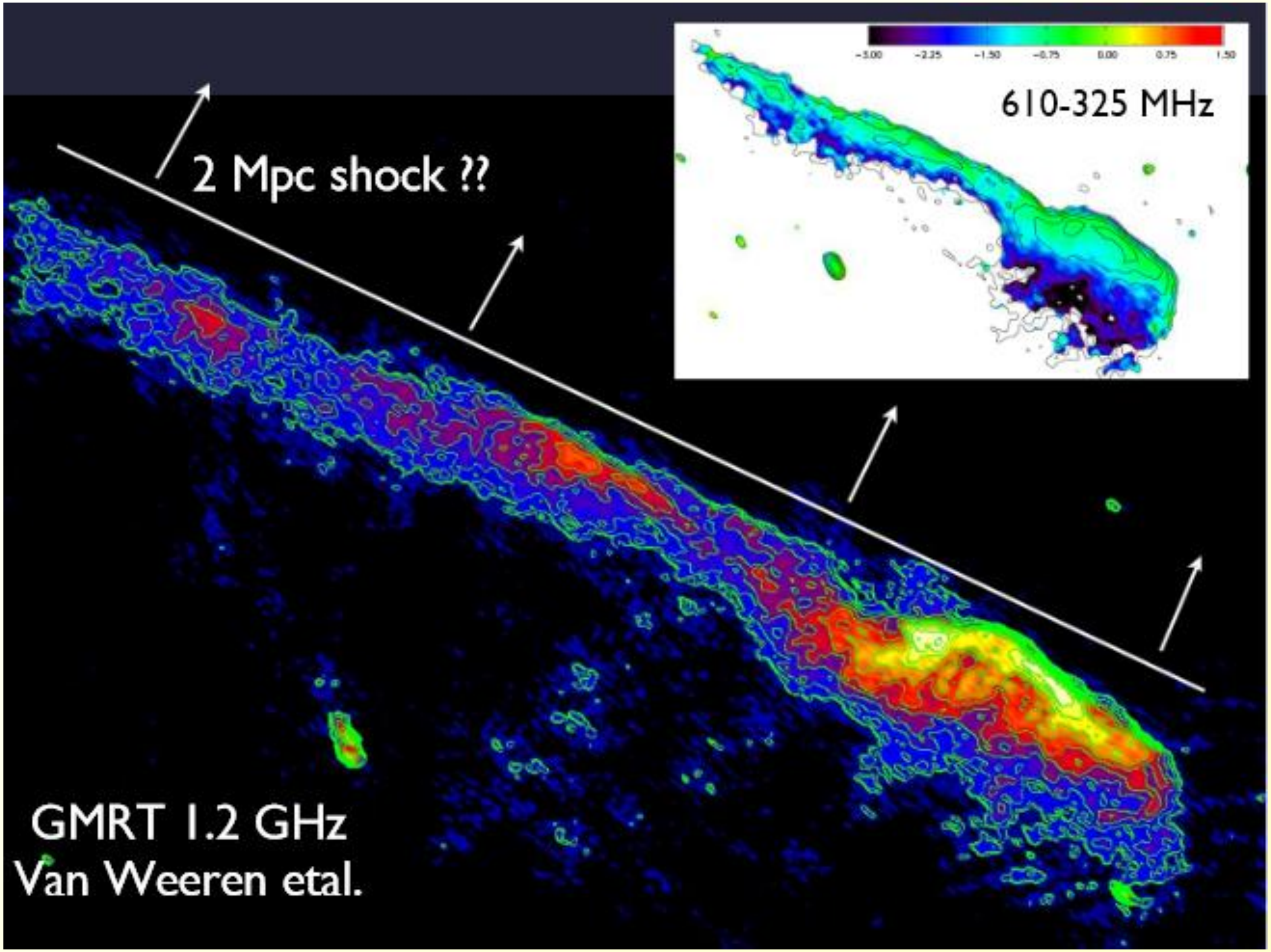
Field of 1 arcmin, z~1

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

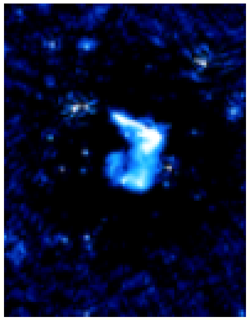


Obreschkow et al 09

Shocks during cluster mergers



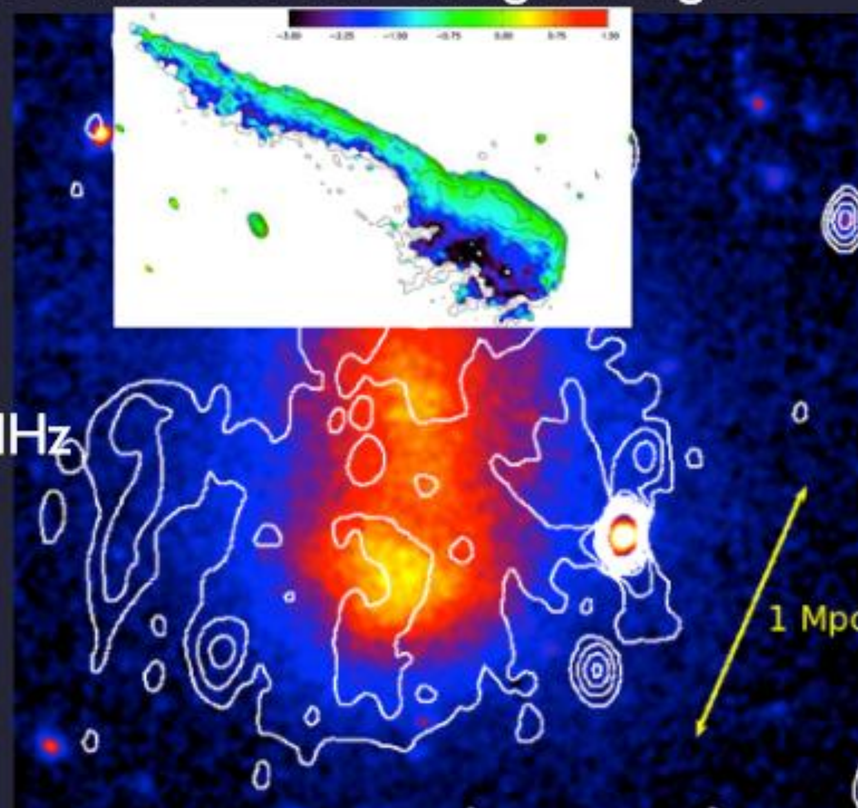
X-ray and radio Synergy



Tooth-brush puzzle:

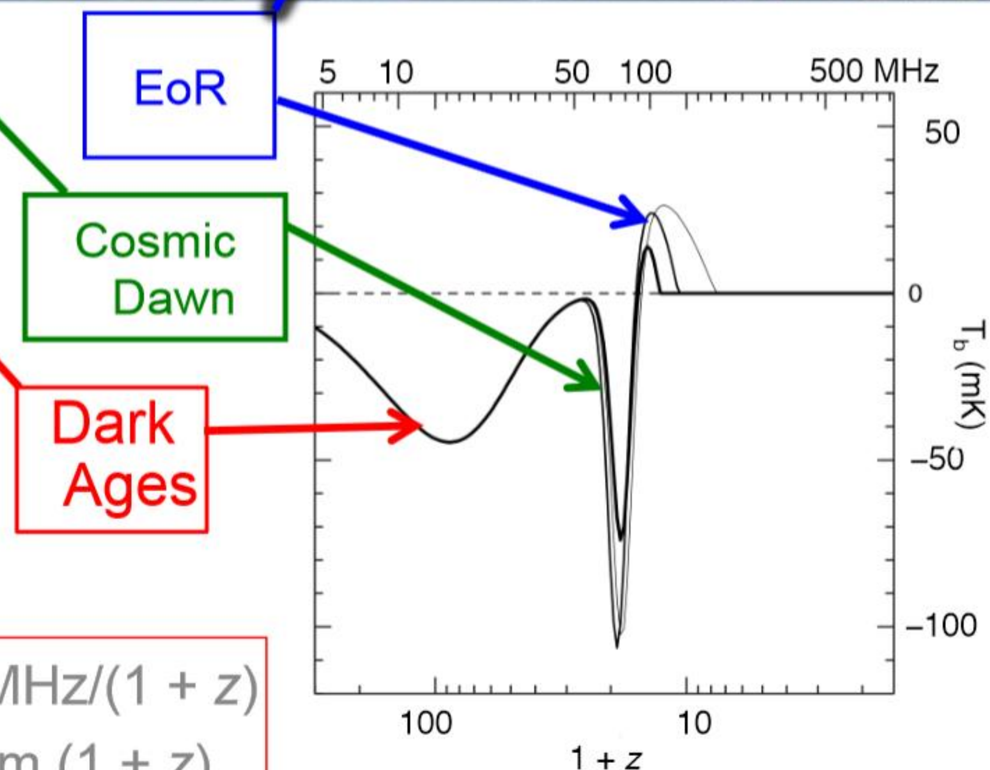
How to produce a linear shock during a merger?

Colours: XMM
Contours: GMRT 610 MHz
green -> blue
spectral index map



LOFAR tells us when clusters up to z=1 are ``relaxed”

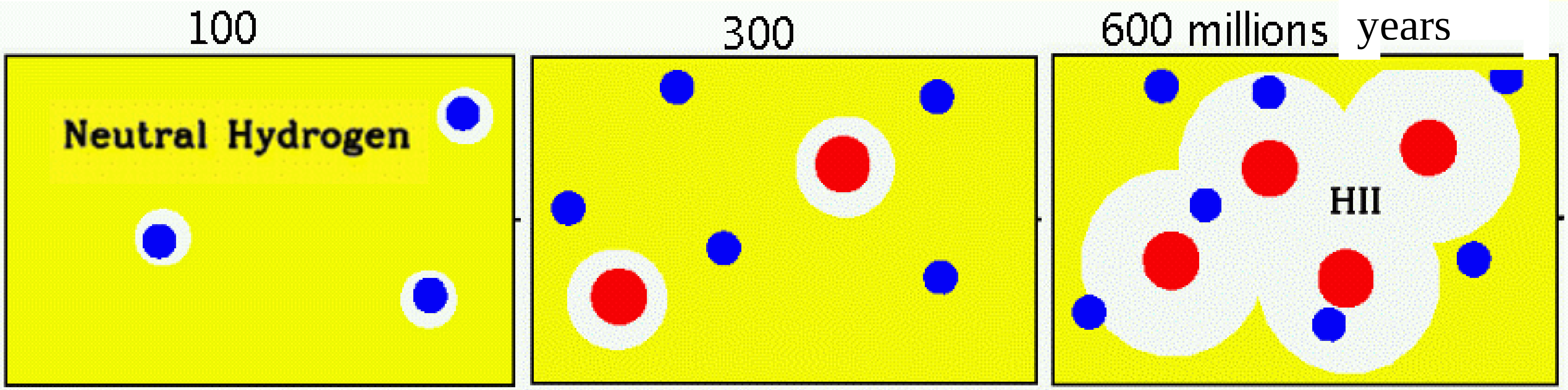
Epoch of Re-ionization: EoR

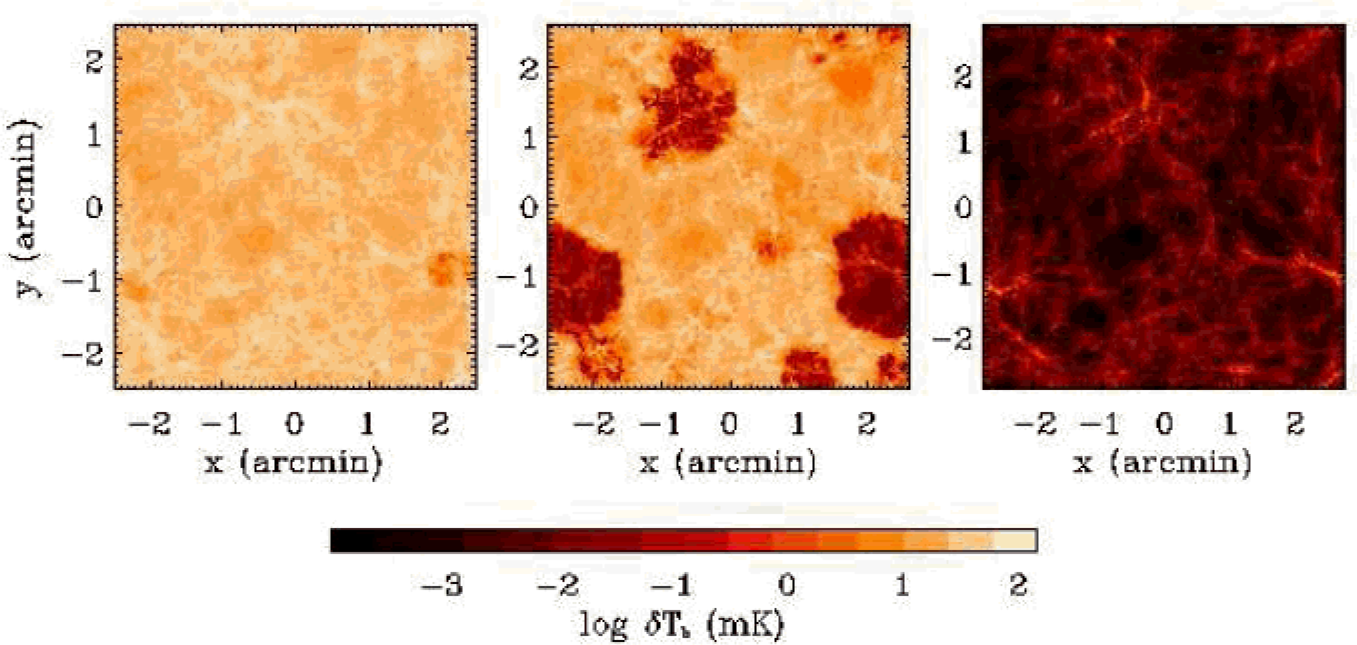


Neutral Hydrogen 21 cm
spin-flip transition provides probe of neutral intergalactic medium before and during formation of first stars

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

Reionization



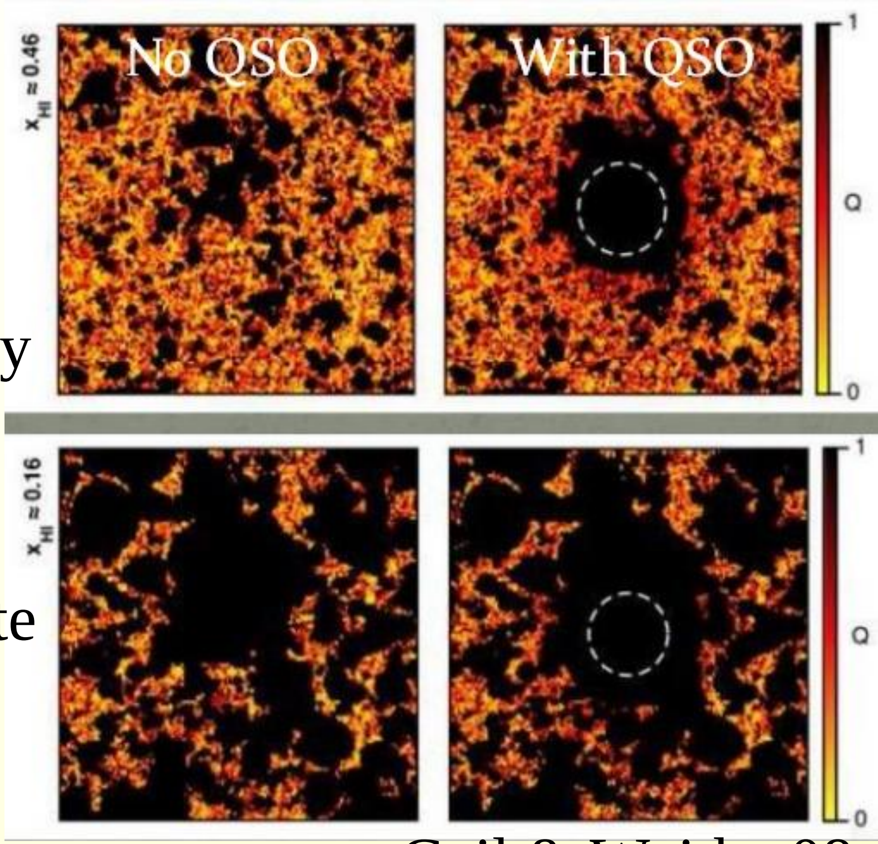


Progressive percolation of ionized zones

Simulations of EoR

Early

Late



Geil & Wyithe 08

Only simulations for now!

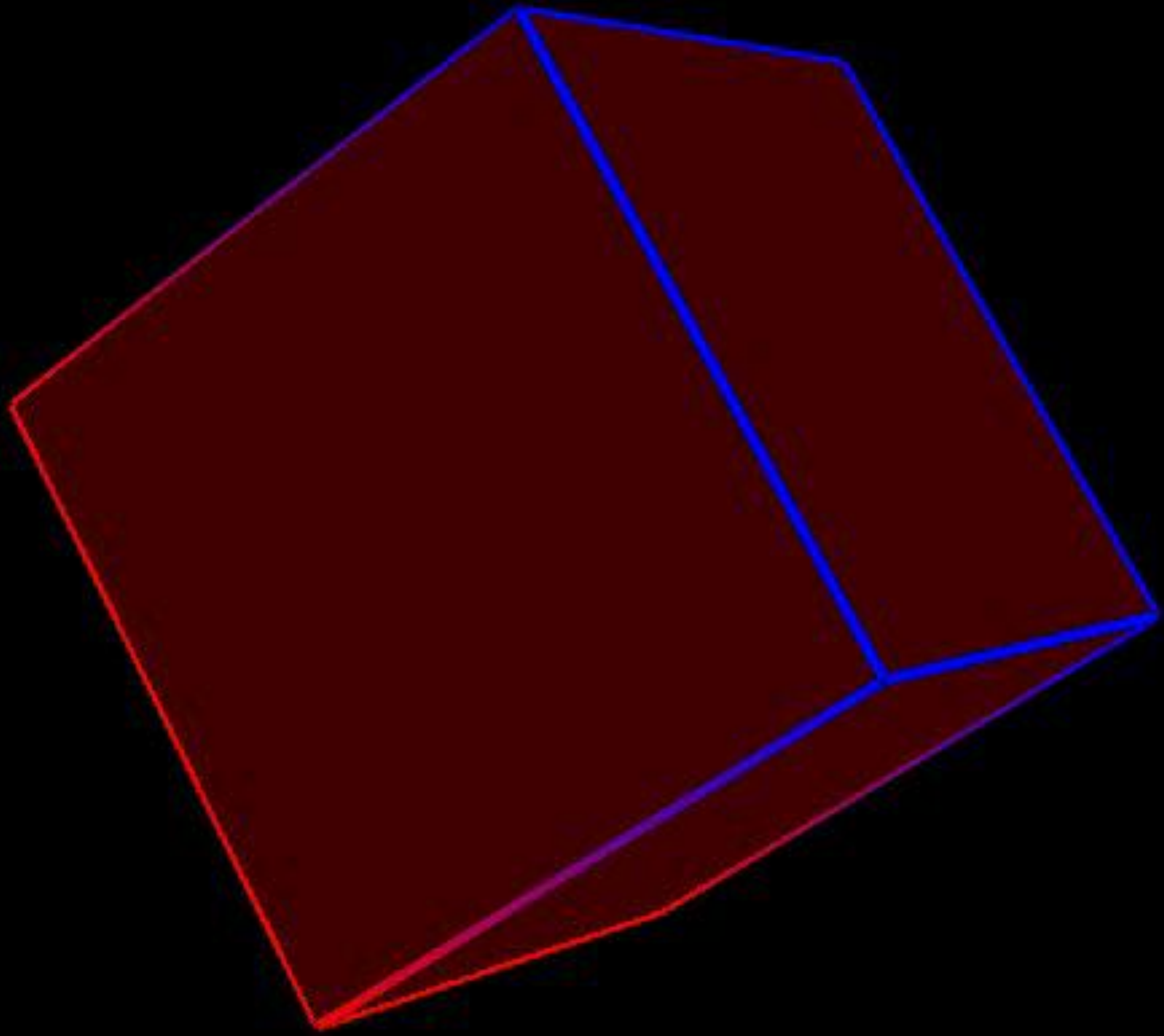
Synergy Euclid /SKA

Discovery of the QSO in the EoR

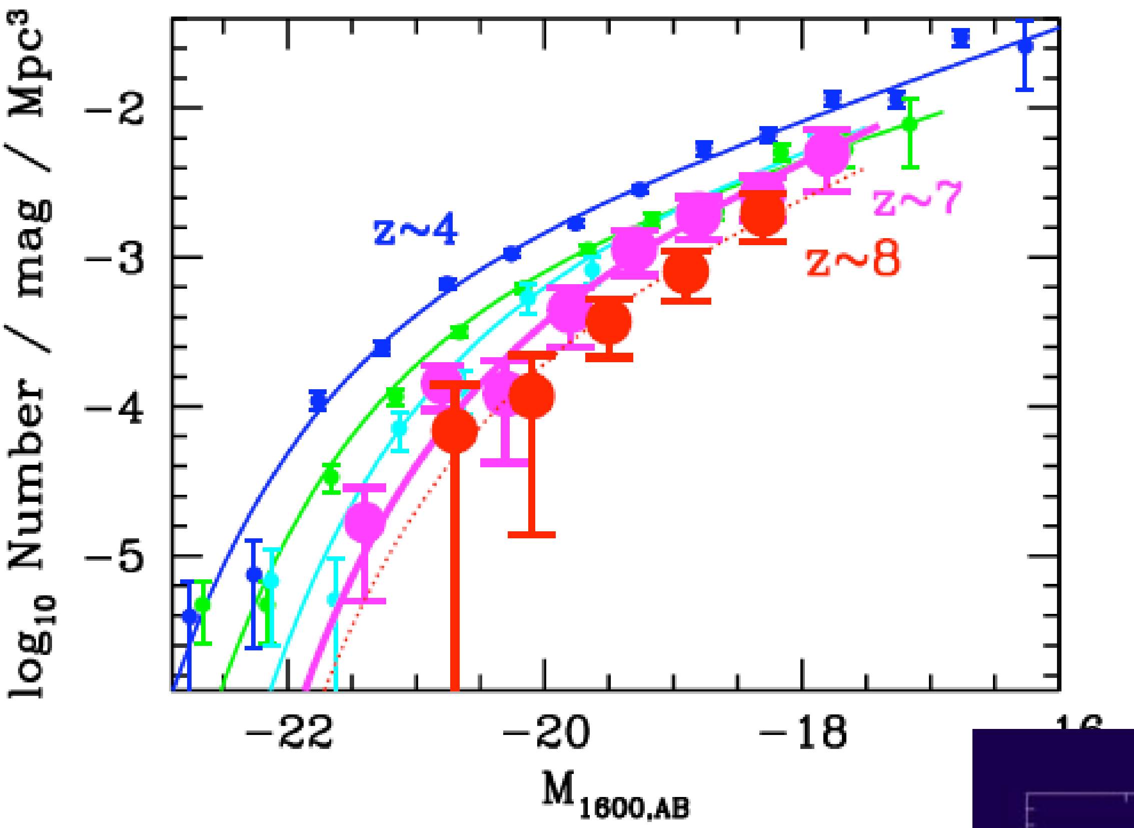
Detection of the HII region around the QSO, at high redshift

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

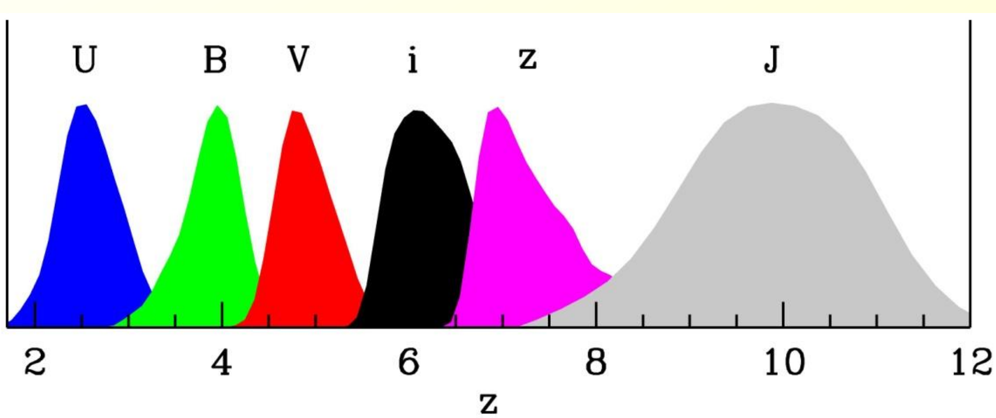
Also absorption studies

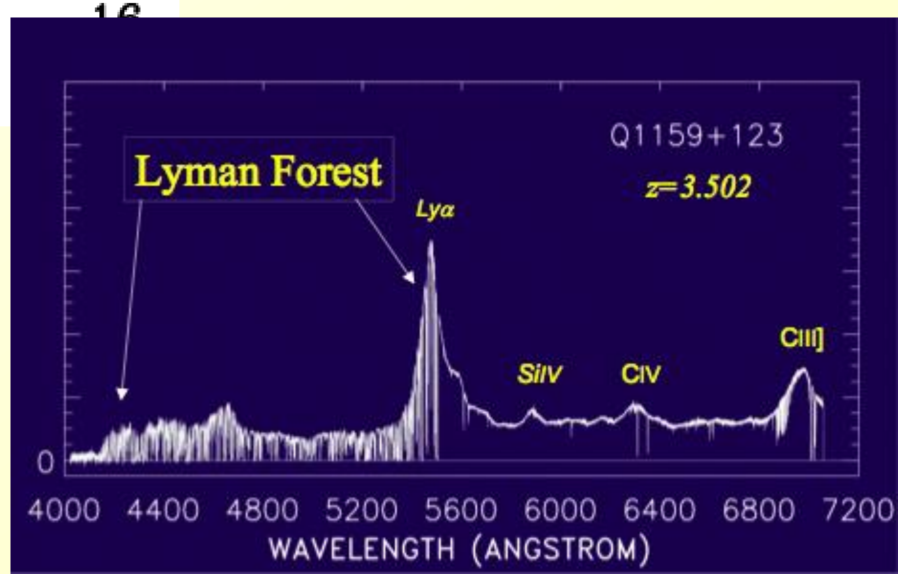


Are galaxies at z=7-10 able to re-ionize?



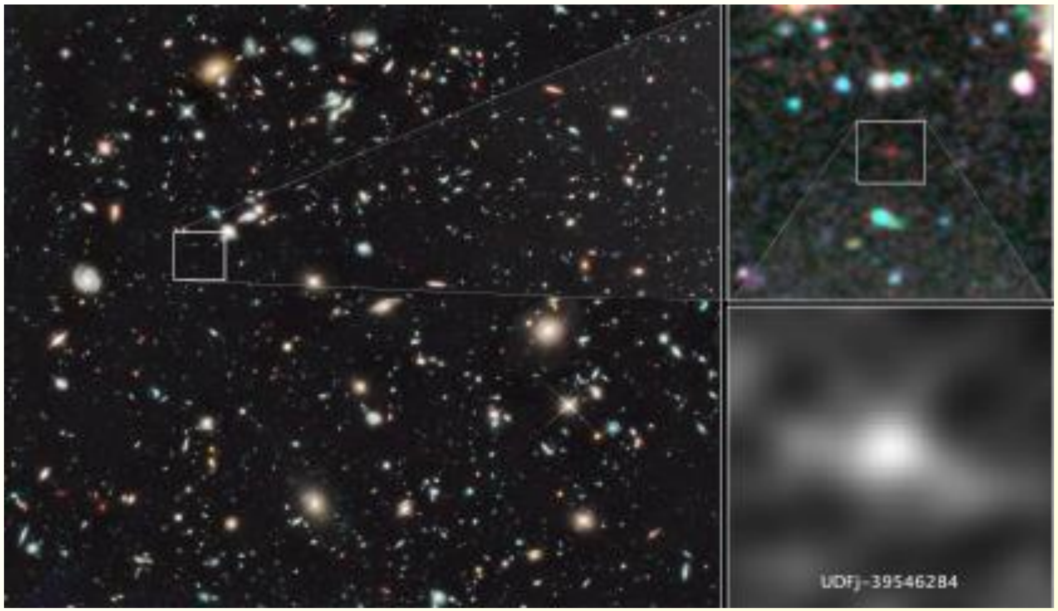
Nbre of galaxies
mag^{-1} Mpc^{-3}

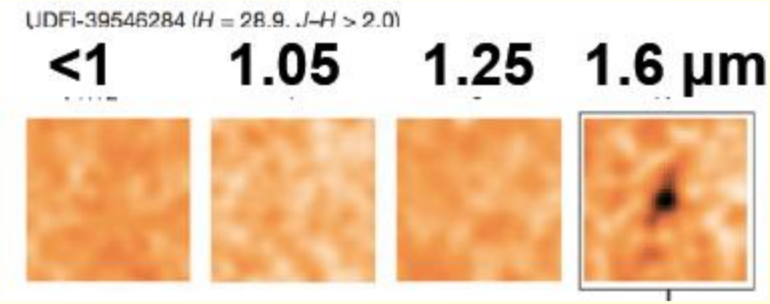




What is the first galaxy?

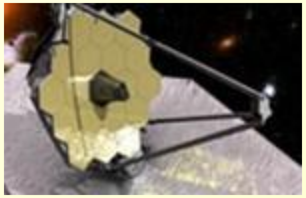
Candidates at z=10

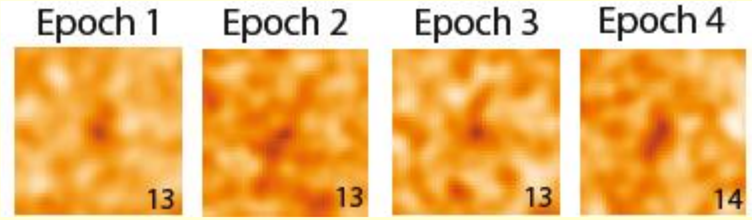




Disappears at λ=1.4 microns

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





Detected in each sub-group
of observations

Galaxy formation and evolution

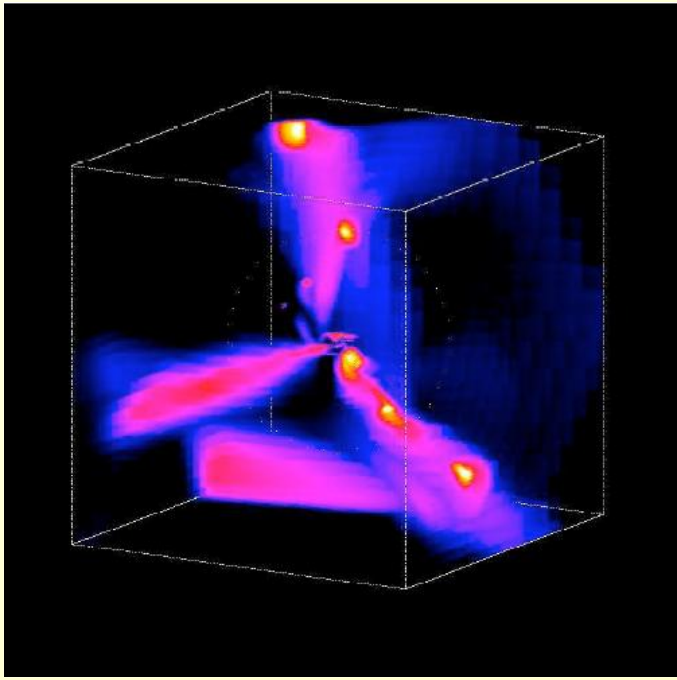
How galaxies assemble their mass?

How much mass assembled in mergers?

How much through gas accretion and secular evolution?

Star formation modes; main sequence,

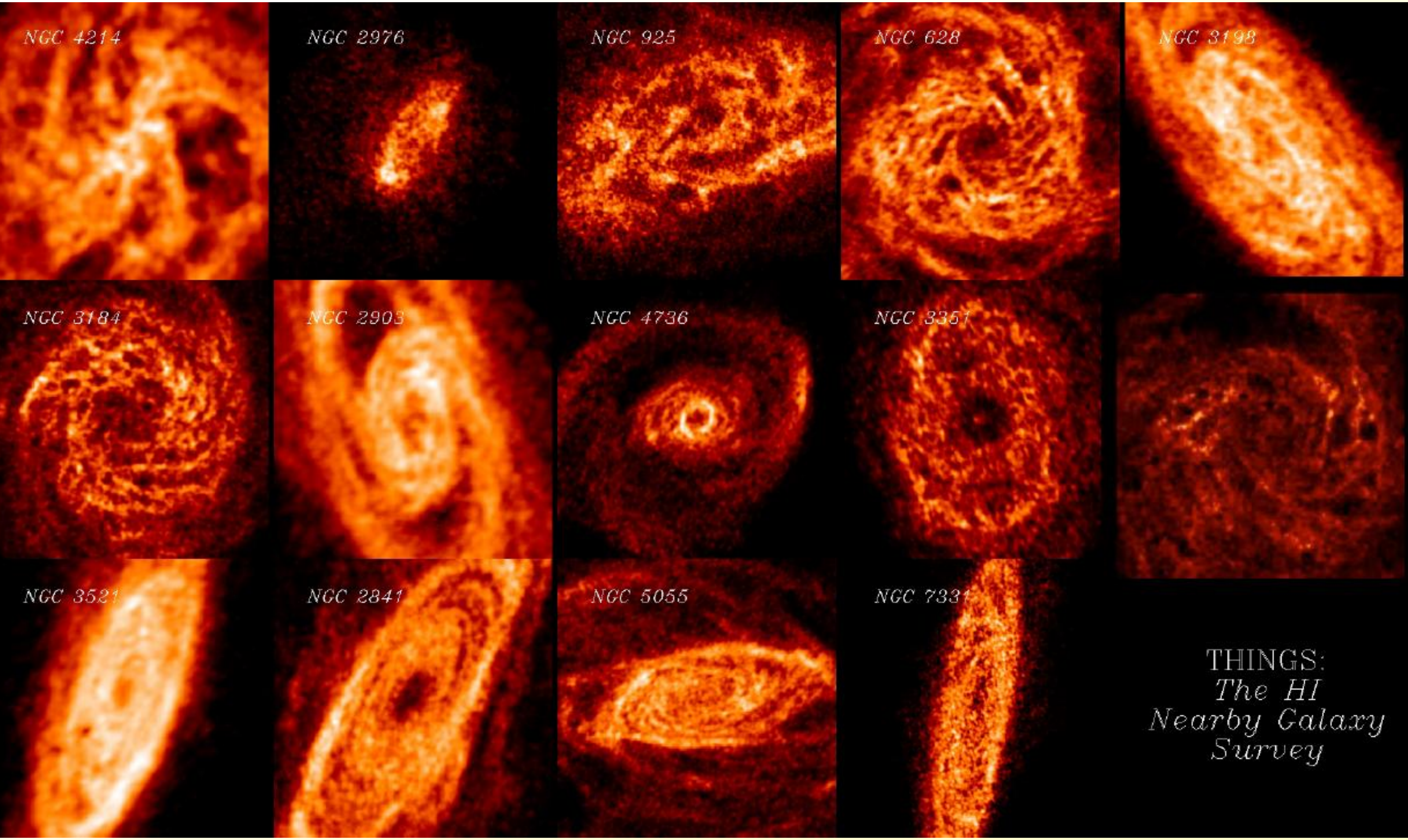
Starburst, mergers?



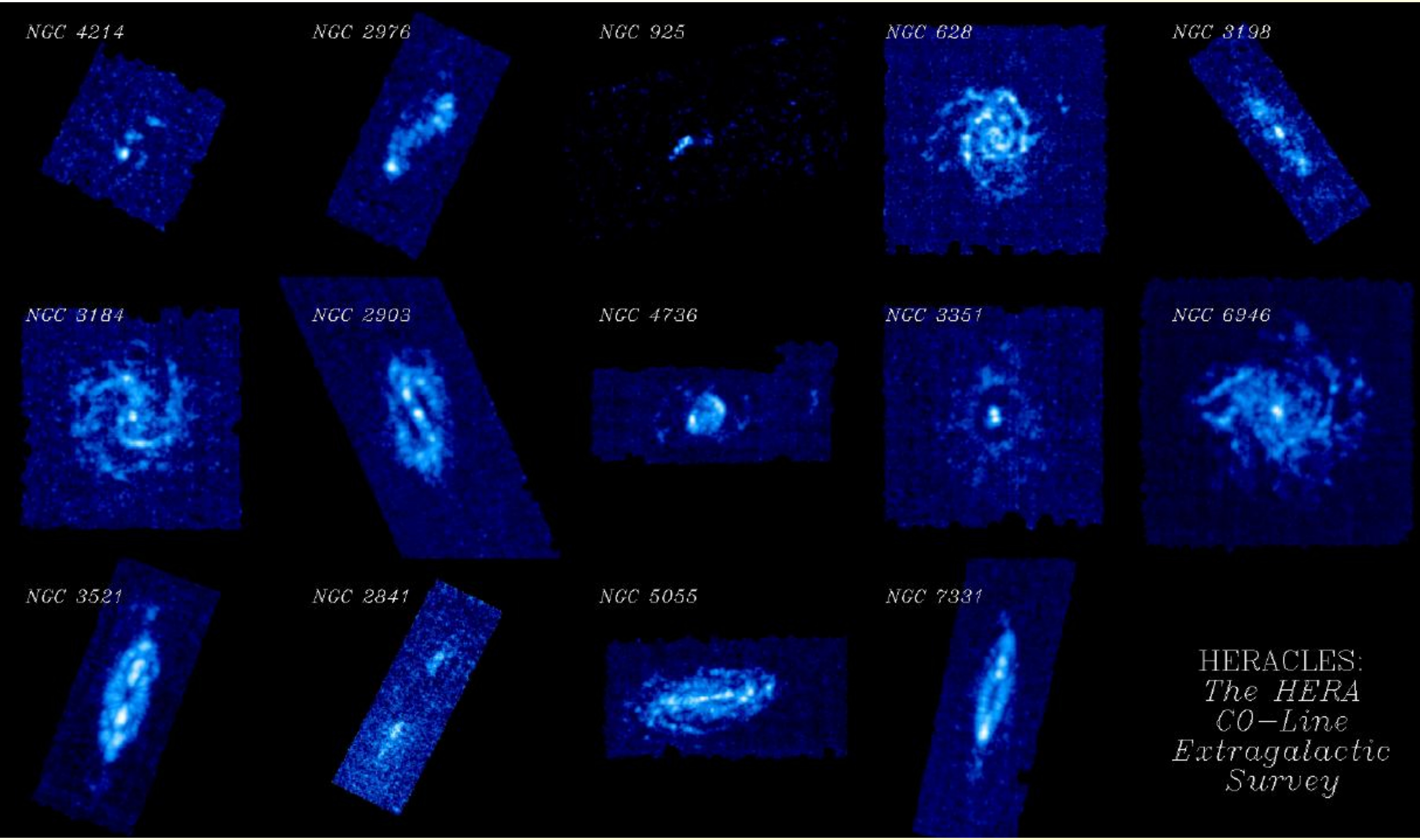
Modes of Quenching

SF and AGN feedback

Atomic hydrogen HI-21cm

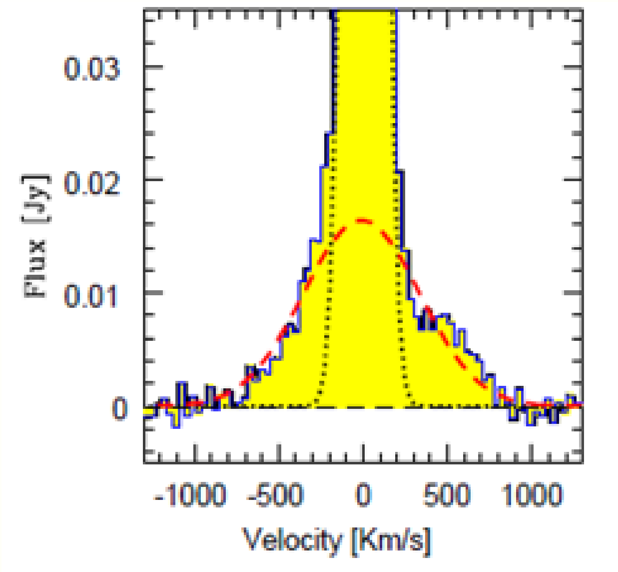


Molecular gas from CO(2-1)

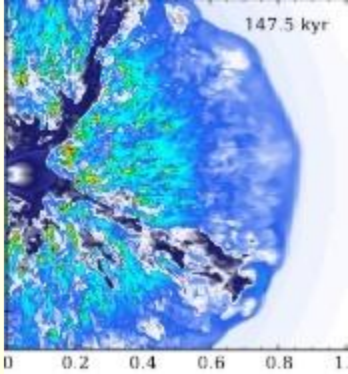


Leroy et al 2013

Black holes in galaxies



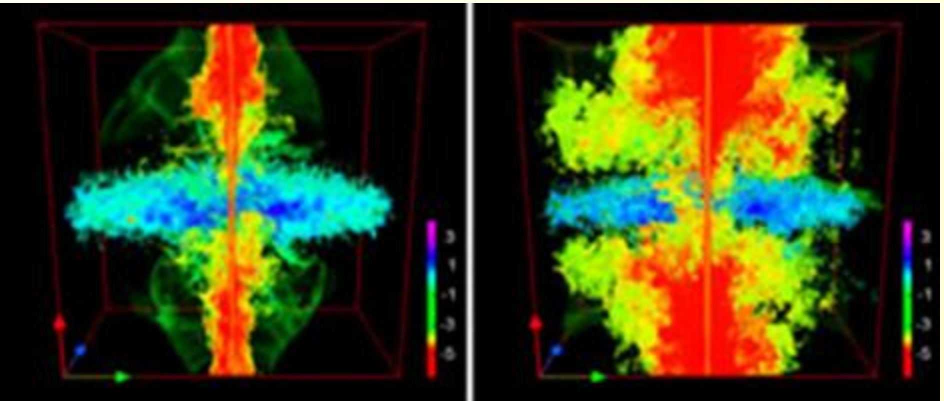
UFO
Wagner et al
2012

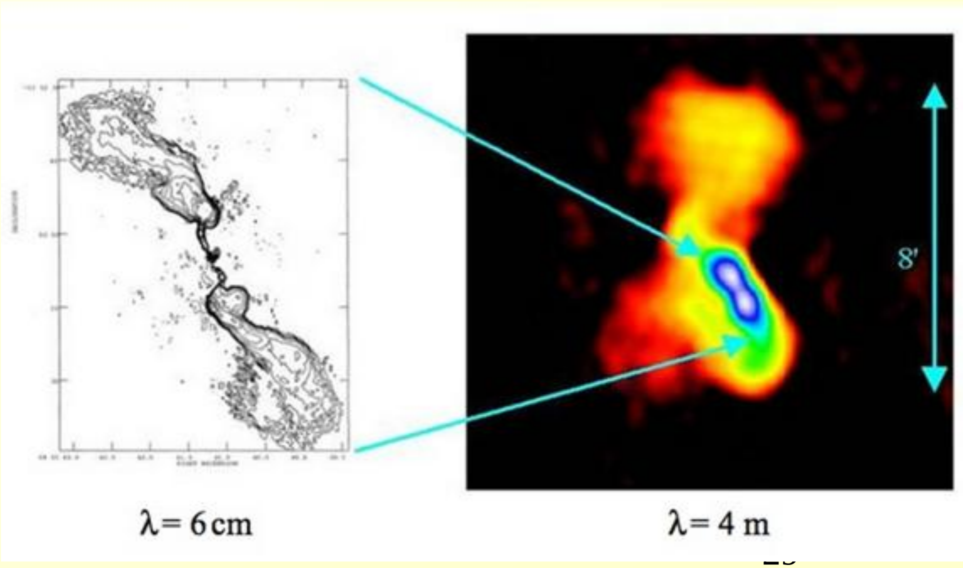


AGN-driven outflow in Mrk 231

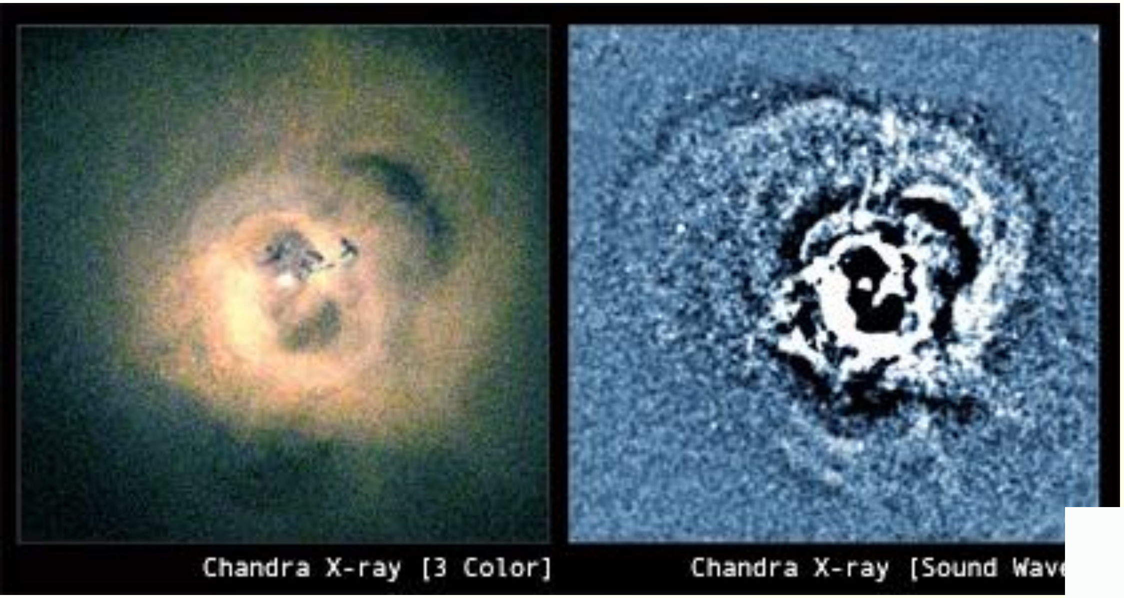
AGN and starburst,
Outflow 700Mo/yr

IRAM *Ferruglio et al 2010*

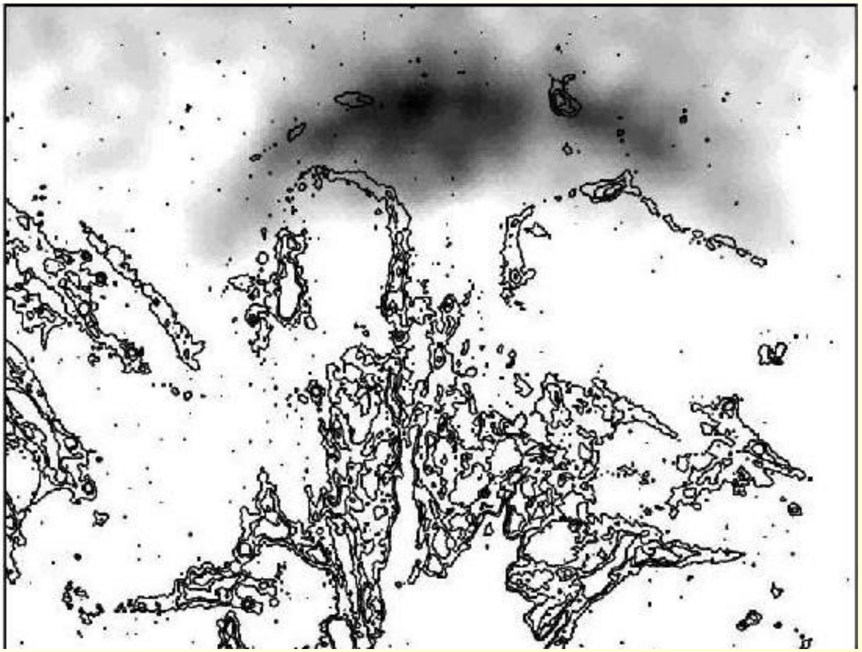




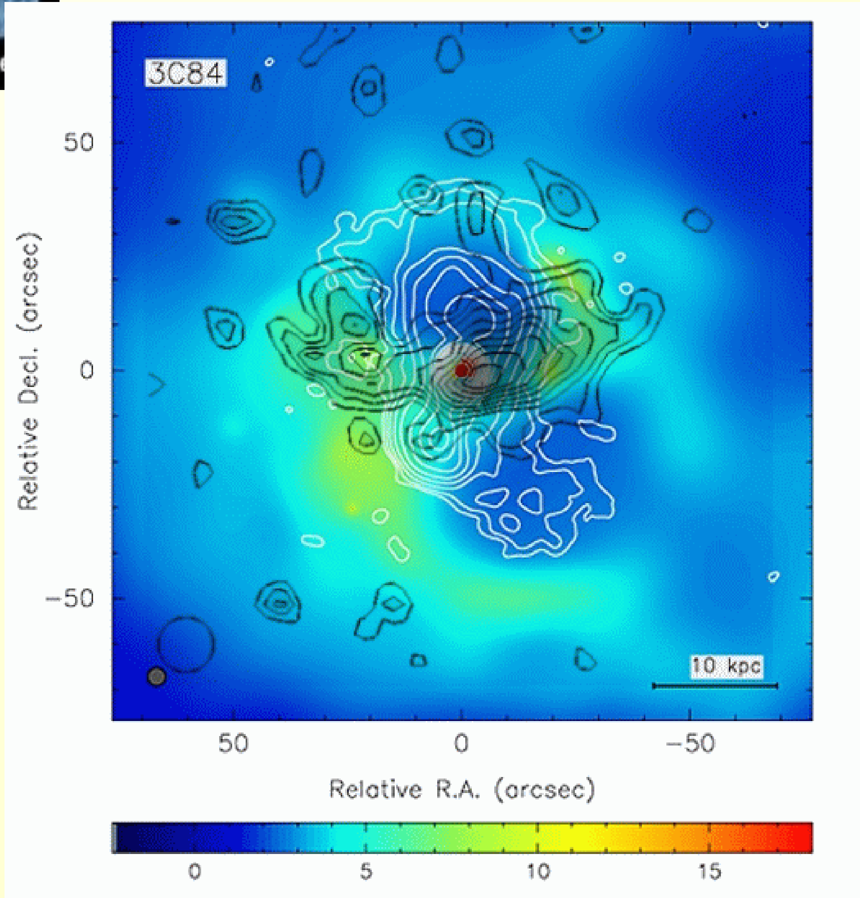
Perseus cool core cluster



Perseus A , *Fabian et al 2003*

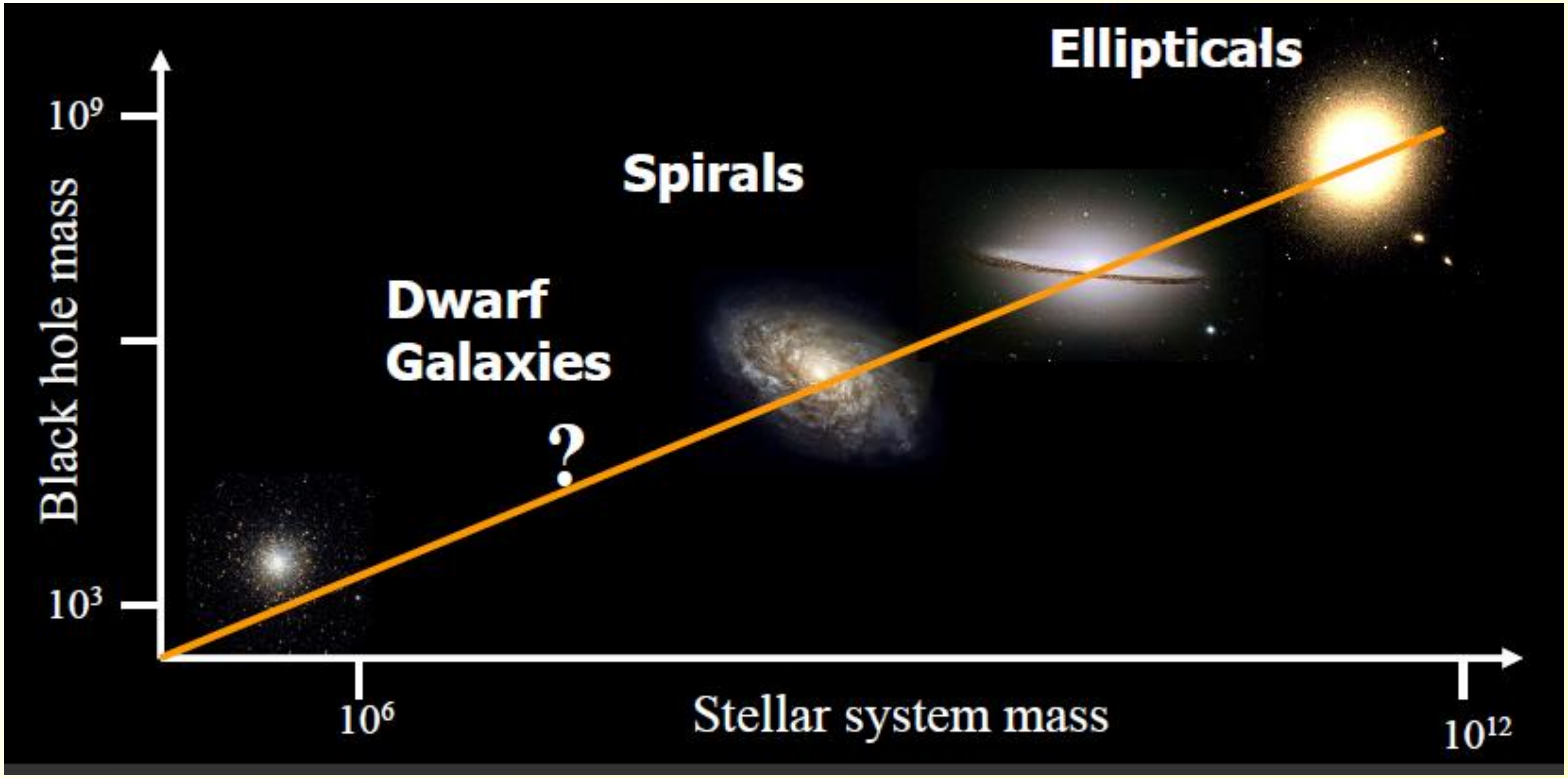


Salomé et al 2006



Not all black holes have been seen!

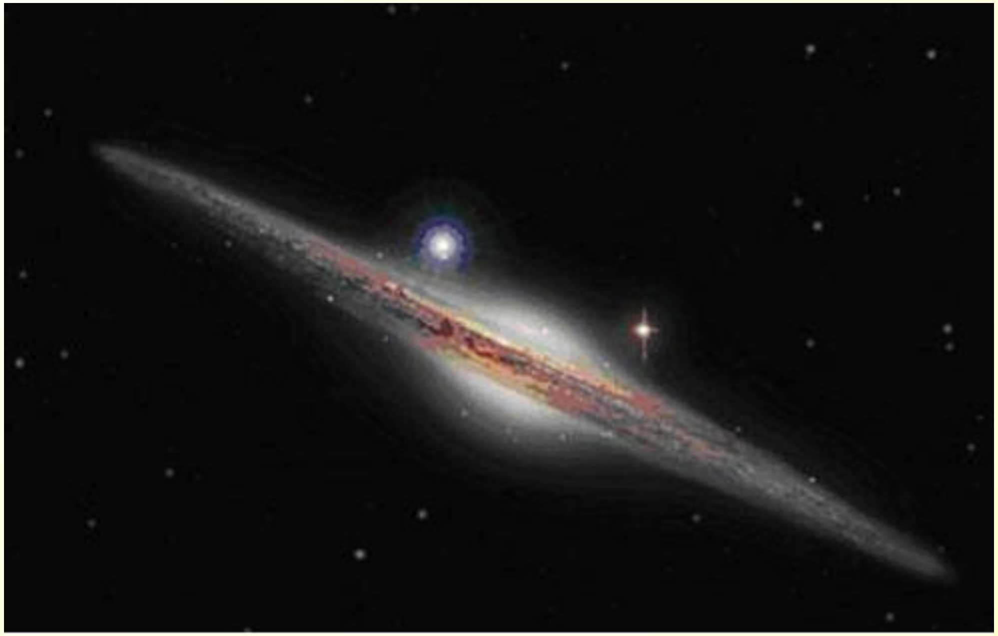
Not massive enough to spiral into the nuclei



HLX-1: the first IMBH?

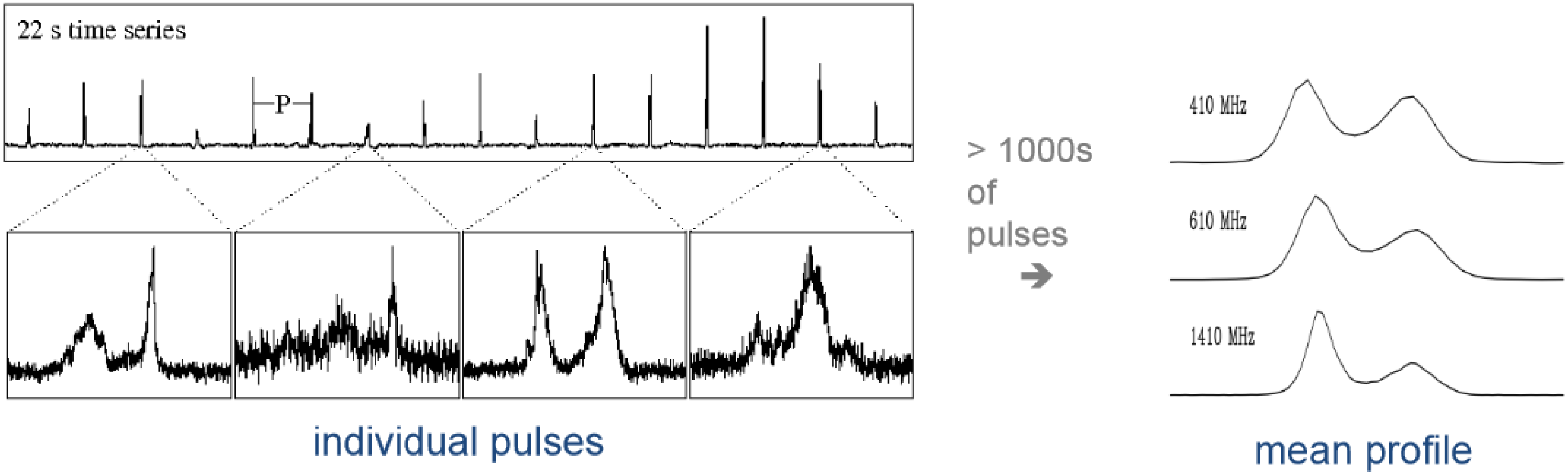
Intermediate-mass black hole (IMBH)?
ULX: Ultraluminous X-ray source

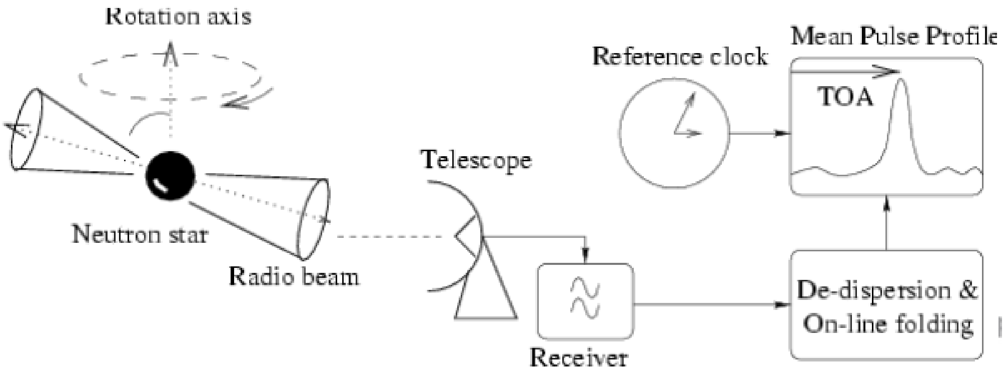
ULX in ESO 243–49, D=95 Mpc, 10^{42} ergs/s, 10^{2}-10^{5} Msun Black hole



Farell et al 2009, Webb et al 2010, Godet et al 2009

Pulsars: Time of Arrival (TOA)



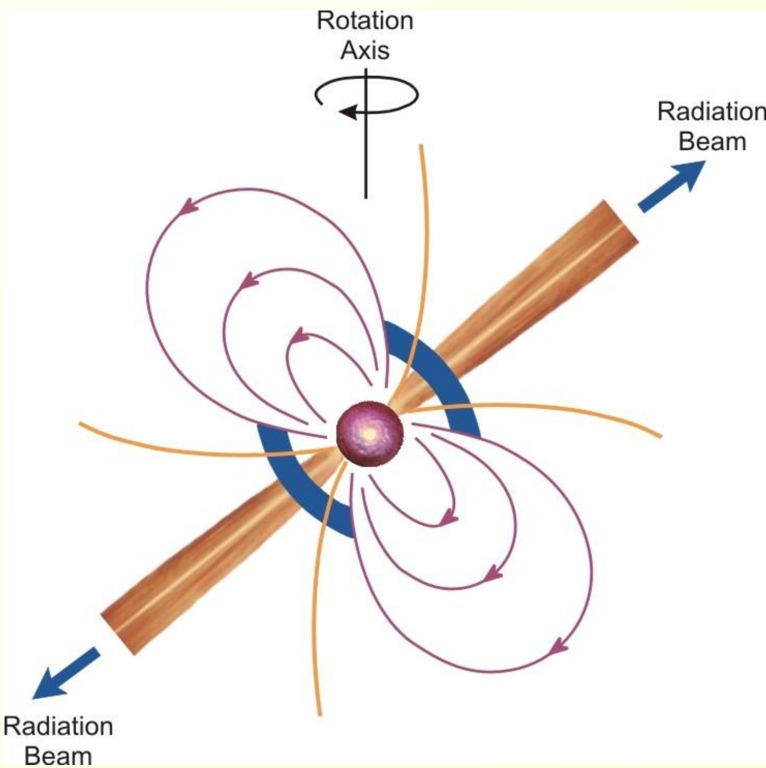


Binaries, and Gravitational waves

From Lorimer & Kramer, *Handbook of Pulsar Astronomy*

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

What are pulsars?



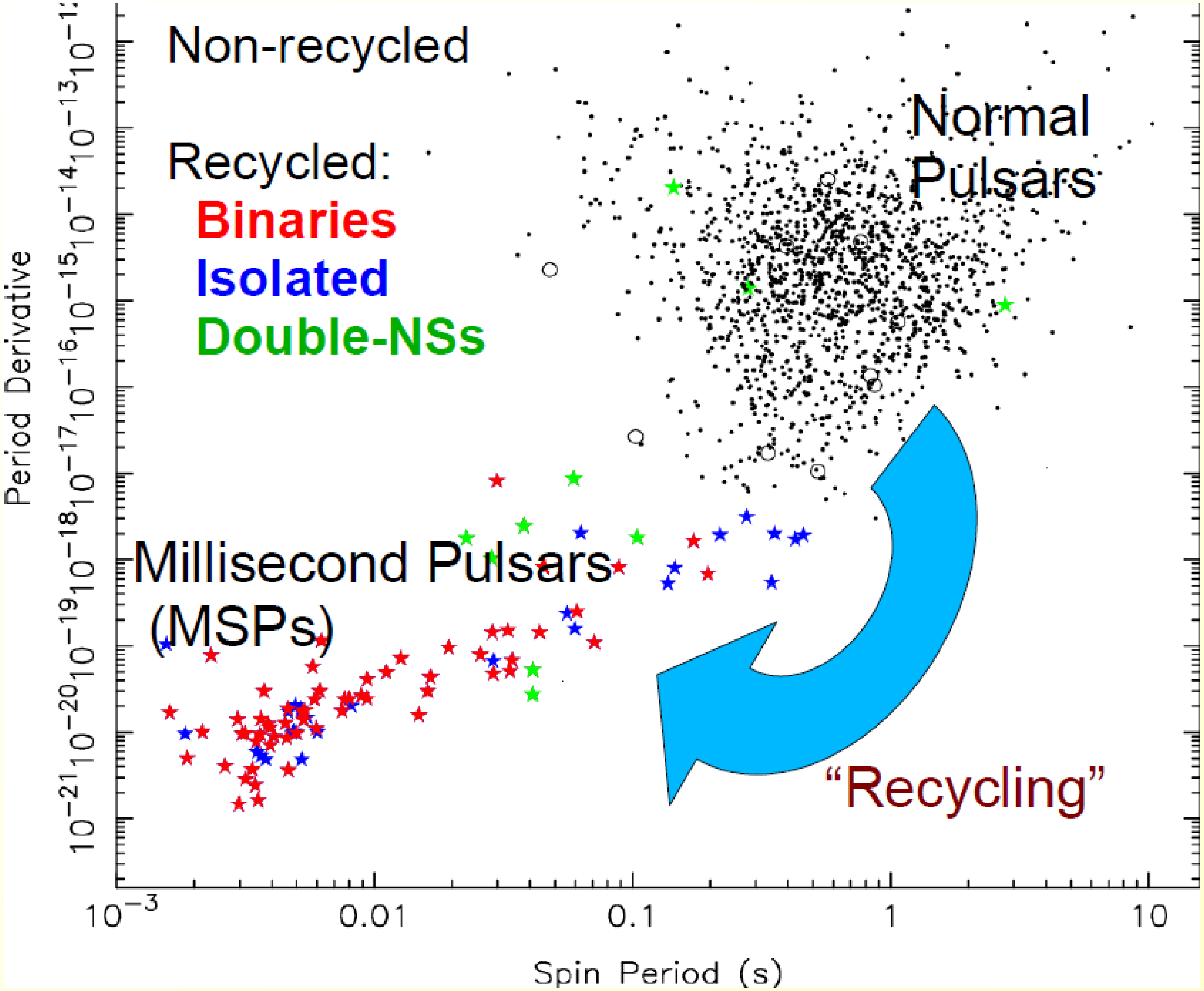
Pulsars are rotating neutron stars,
discovered by Bell & Hewish (1968)
Size ~10km, Mass~1-2 Mo,
Central density > nuclei! (10^{15}g/cm^3)
Surface gravity 10^{11} g,
Magnetic field up to B=10^{12} G

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 (13^{th})
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

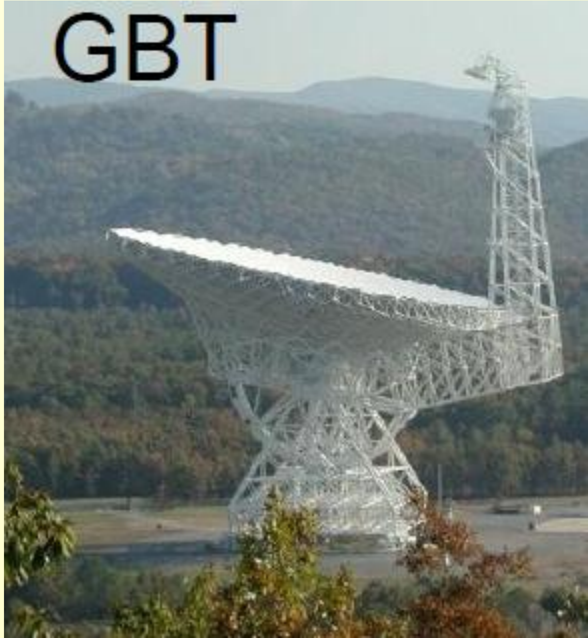
TOA measured with μs during several yrs

➔ 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)



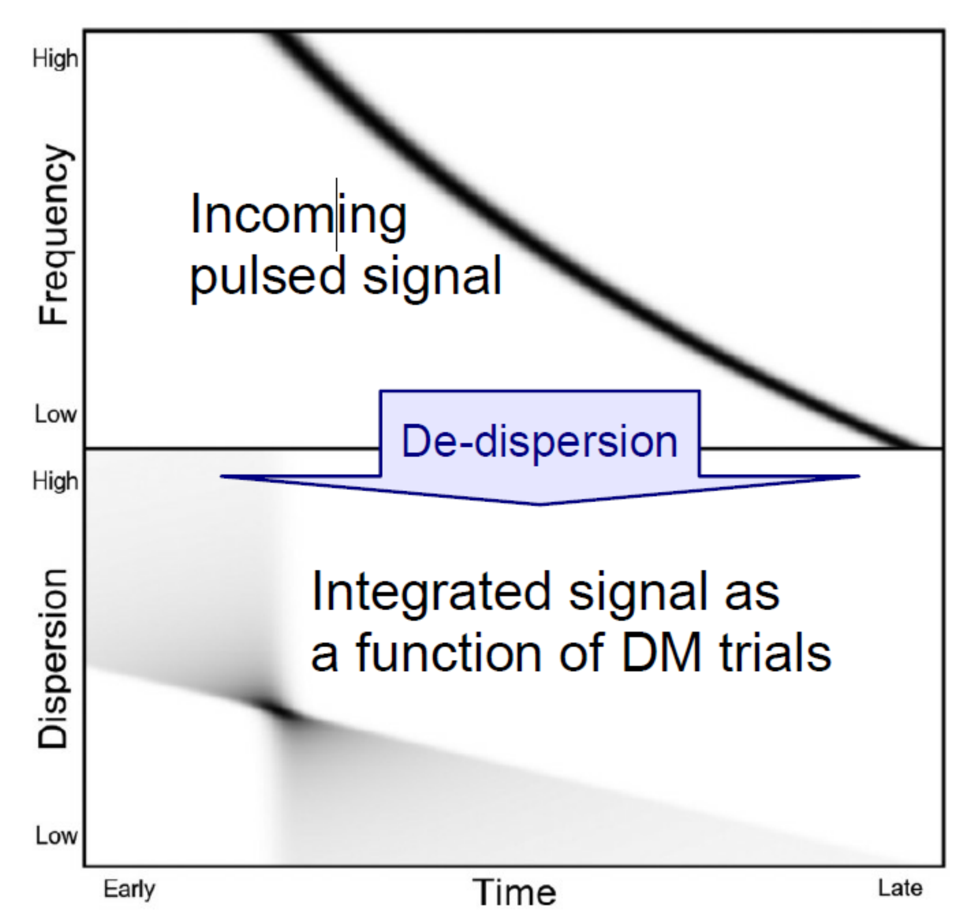
When the binary is edge-on: case of J1614-2230
Gravitational delay when MSP behind white dwarf
➔ Shapiro delay
8.7 days orbit, 30 μs delay of the pulses!
Observed with GBT-GUPPI
GPU and FPGA to process the signal

The dispersion problem

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

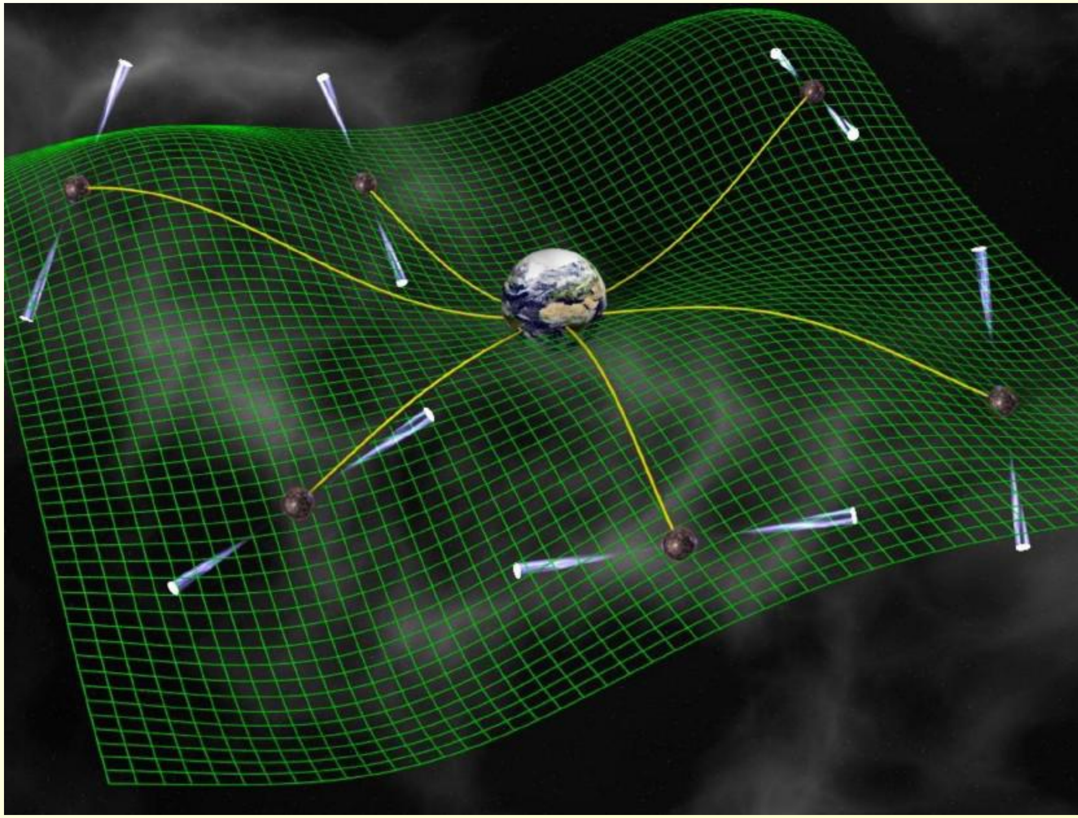
Barsdell et al 2012

- 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

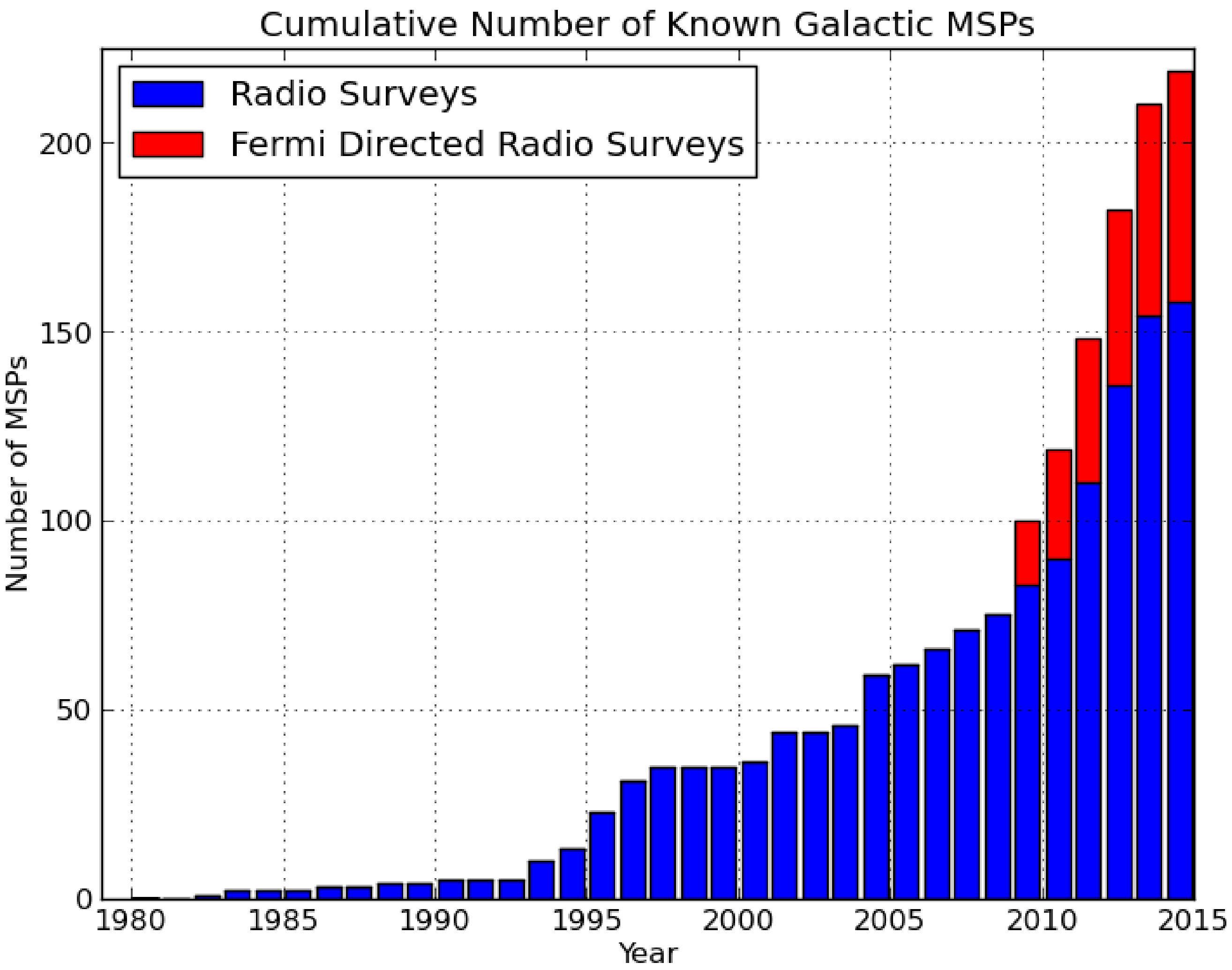


➔detect GW before LIGO ?

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

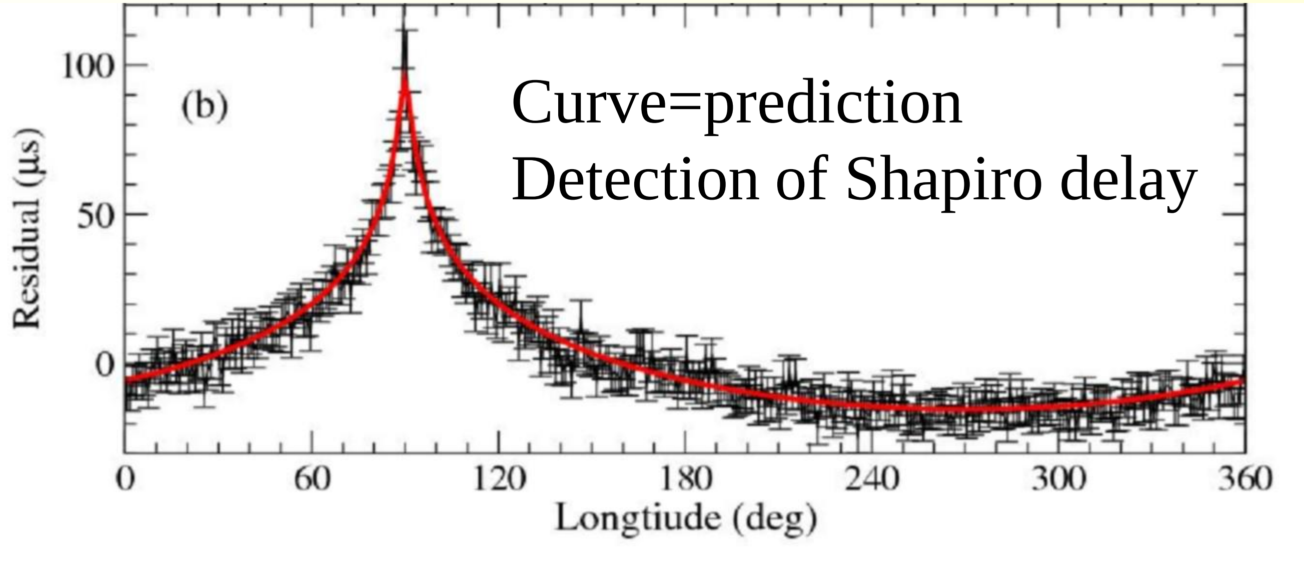
Cannot re-analyse
➔ Re-observe

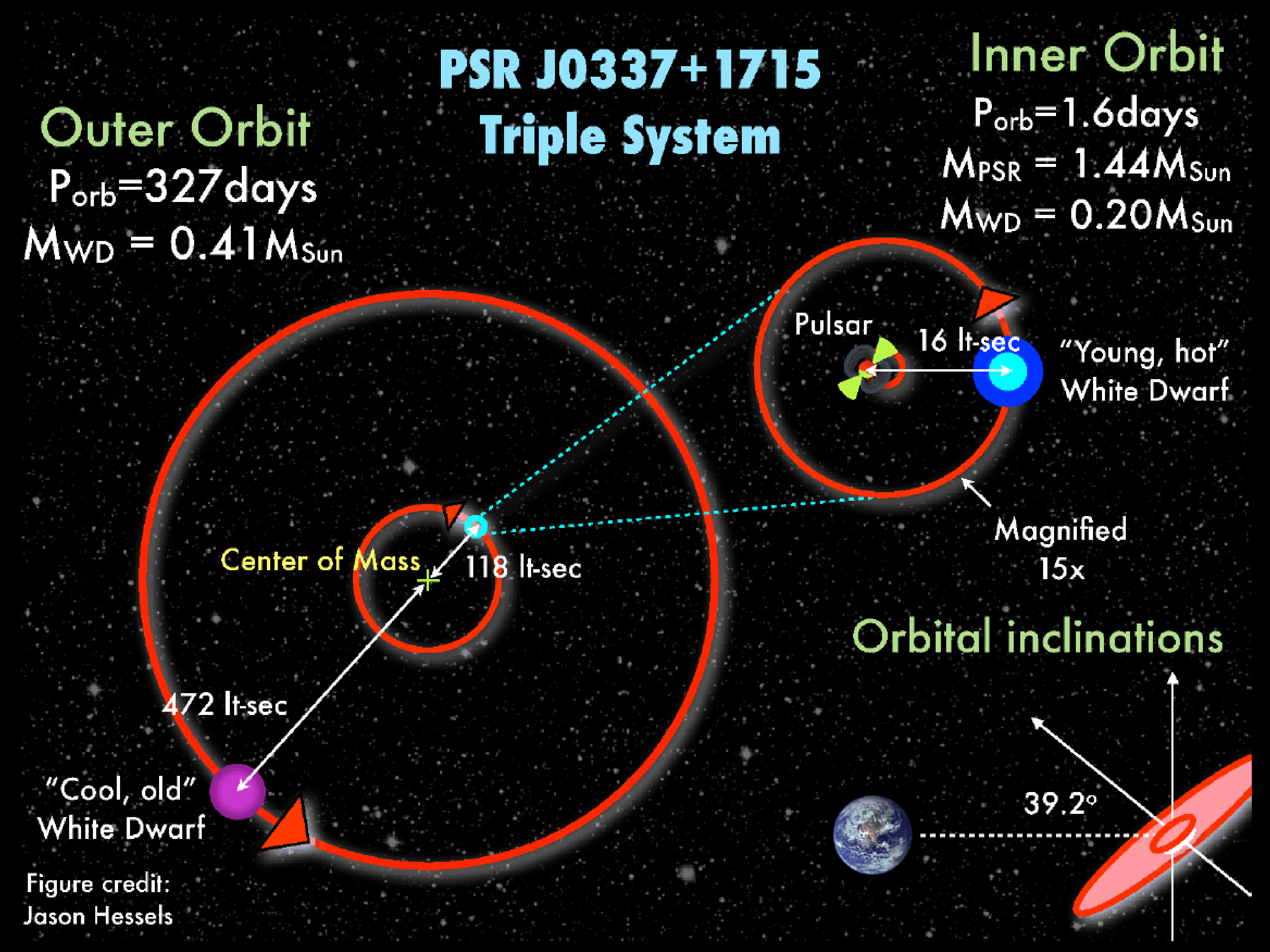
Tests of General Relativity

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

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



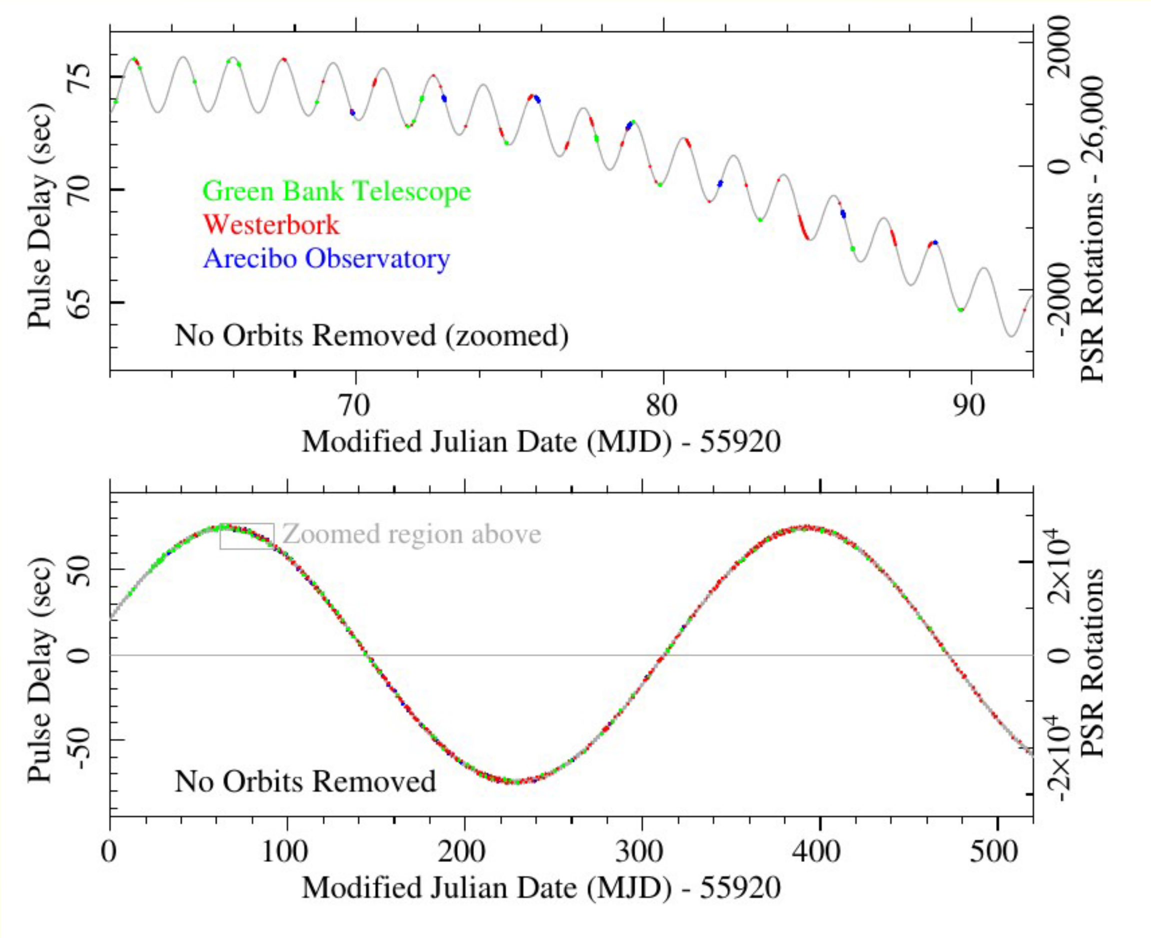


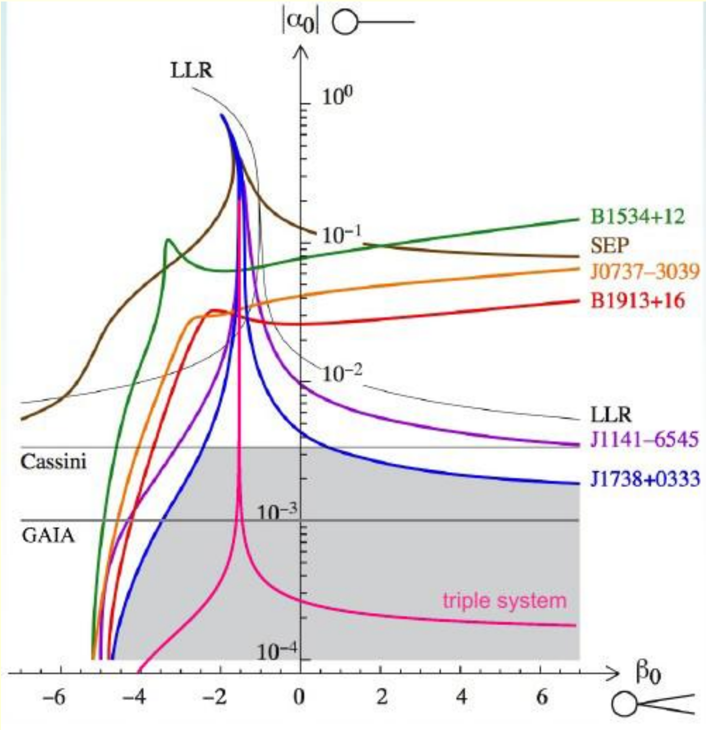
PSR J0337+1715
Triple System
Outer Orbit
P_{orb}=327days
M_{WD} = 0.41M_{Sun}
Inner Orbit
P_{orb}=1.6days
M_{PSR} = 1.44M_{Sun}
M_{WD} = 0.20M_{Sun}
Pulsar
16 lt-sec
"Young, hot" White Dwarf
Magnified 15x
Center of Mass
118 lt-sec
472 lt-sec
"Cool, old" White Dwarf
Orbital inclinations
39.2°
Figure credit: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

Precise data from the triple system

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

Other scalar-tensor theories
GR: $\alpha0=\beta0=0$

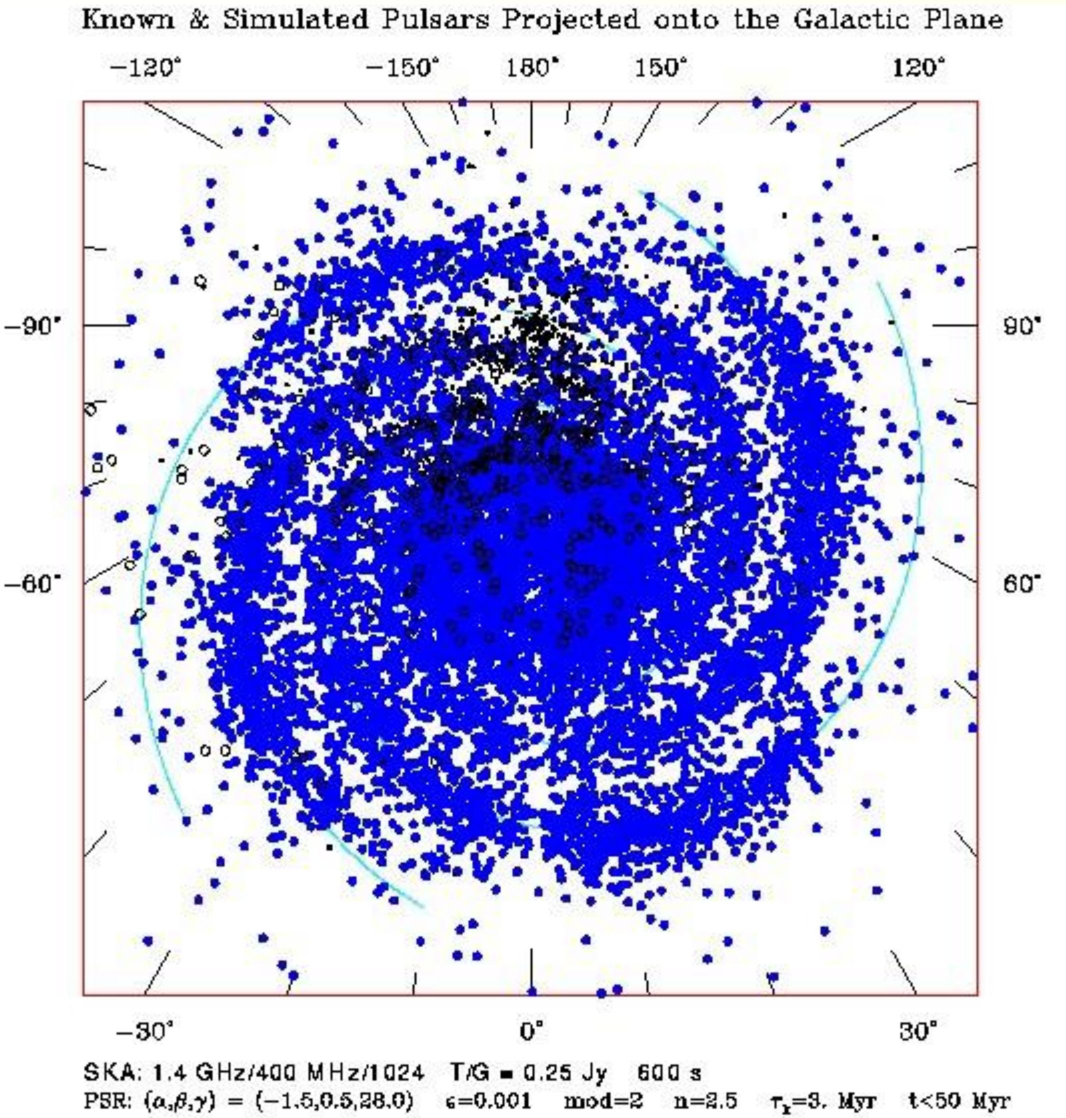




Archibald et al 2014

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

Goal -- Definition

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

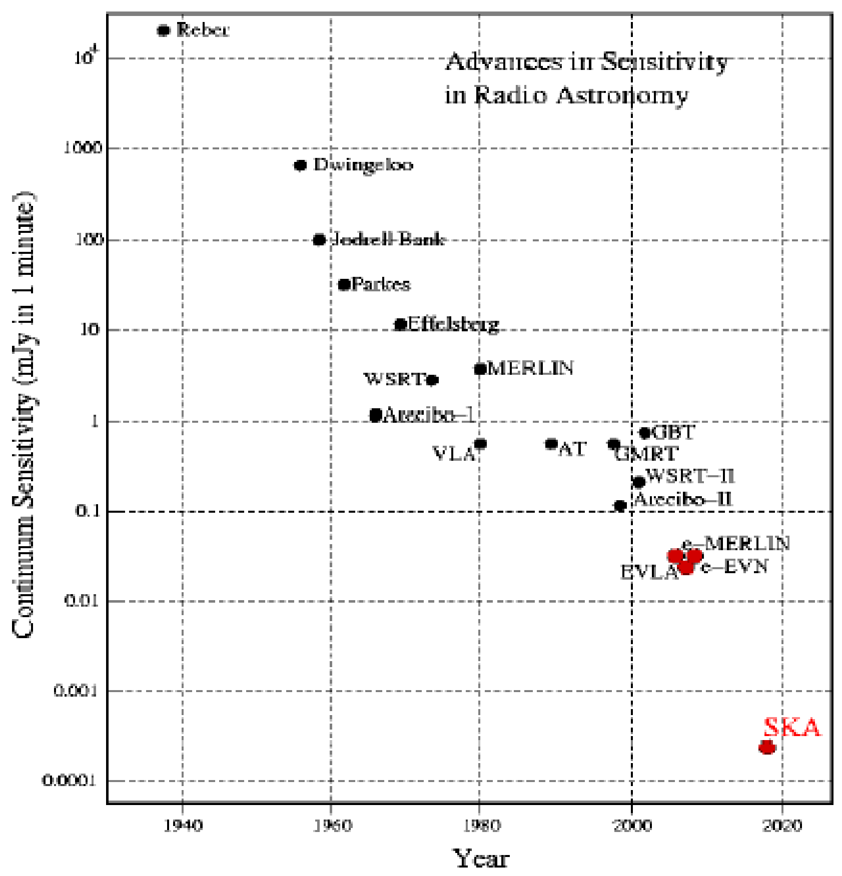
- **one square kilometre collecting surface**

50-100 x more sensitive than present radio telescopes
for *spectral line* observations
1000 x more sensitive than present radio telescopes
for *continuum* observations

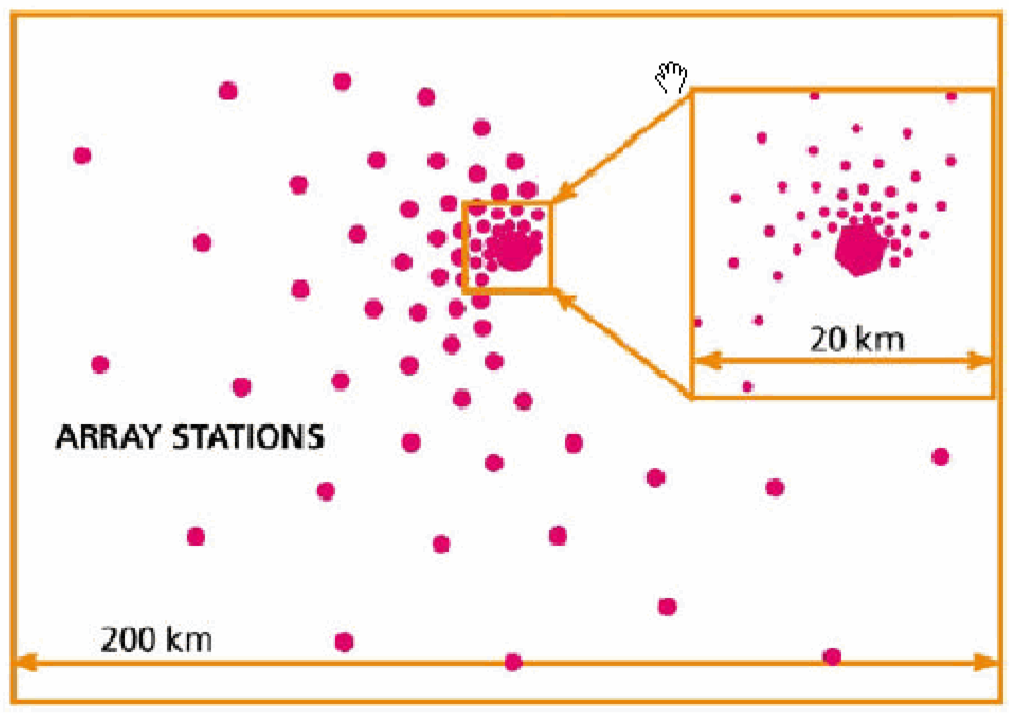
- frequencies: 70MHz – 25 GHz (λ 1.2cm – 4m)
- field of view: 1 (→ 100?) square degrees at λ 21 cm / 1.4 GHz
  8 independent fields of view
- angular resolution: 0.01 arcsec at λ 21 cm / 1.4 GHz

→ baselines up to ~ 3000 km

SENSITIVITY

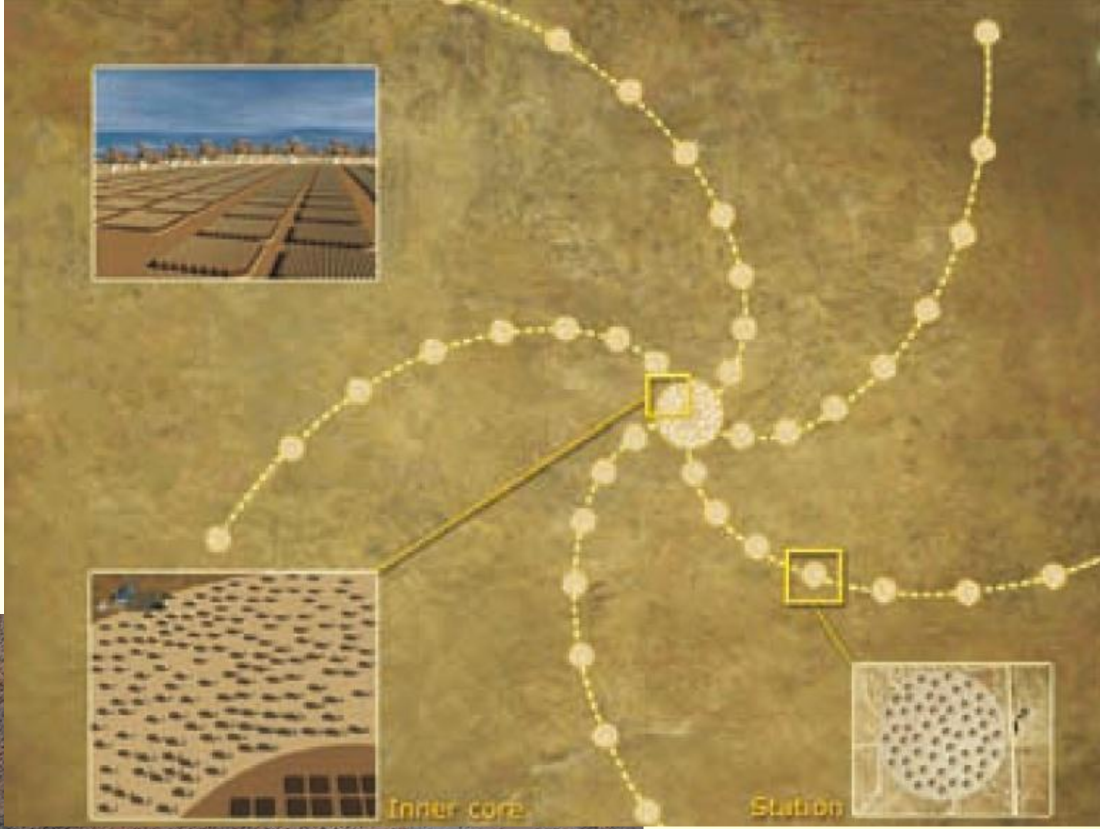


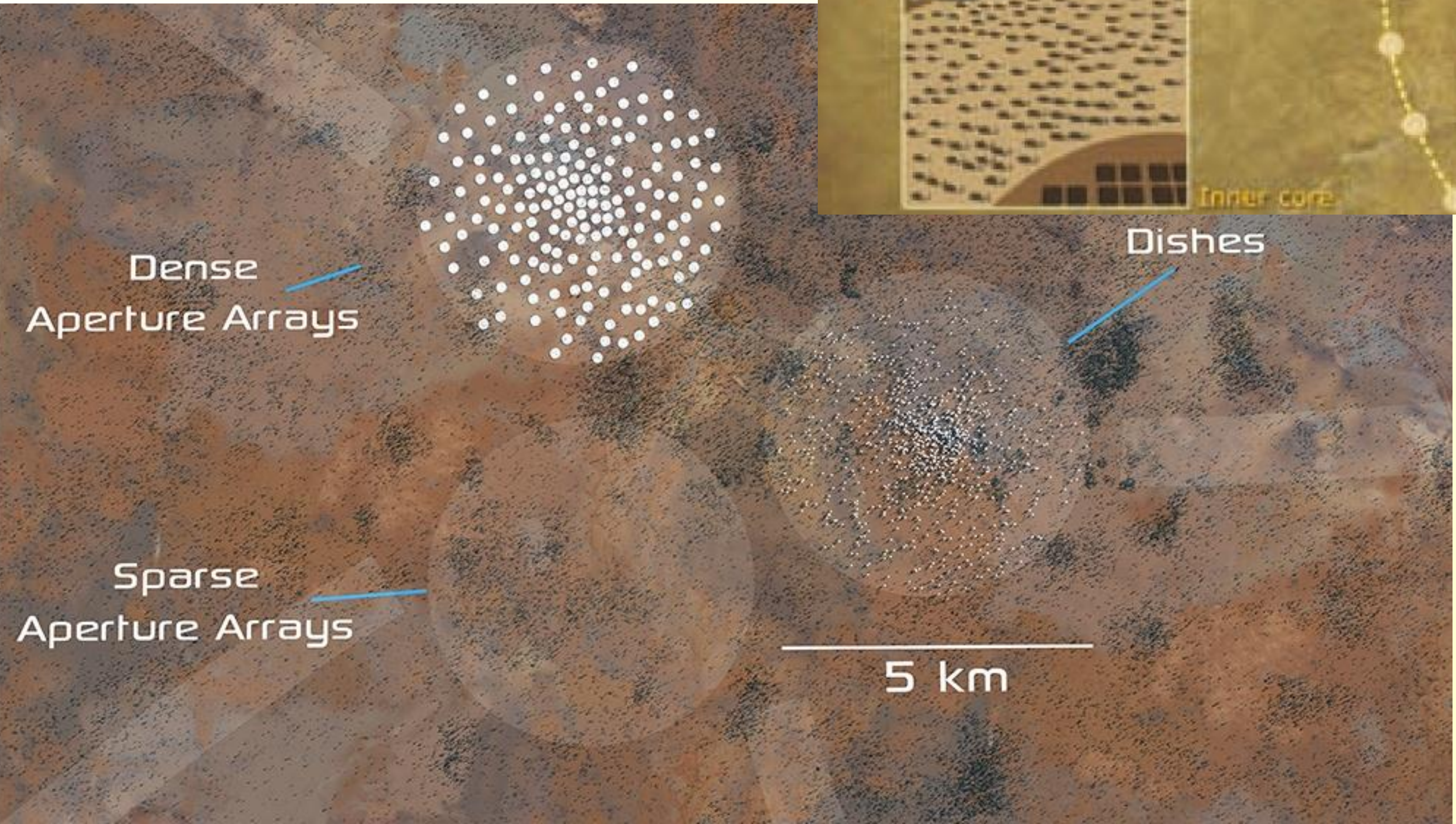
Point source sensitivity of
10 nano-Jy in 8hours



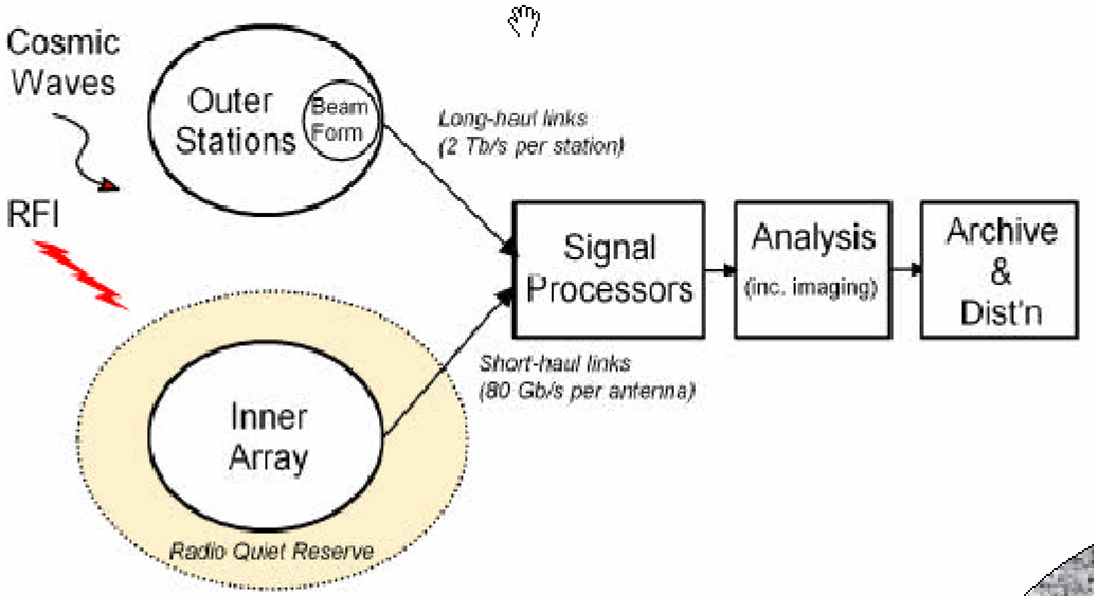
CONFIGURATION

Presently foreseen disposition of the core

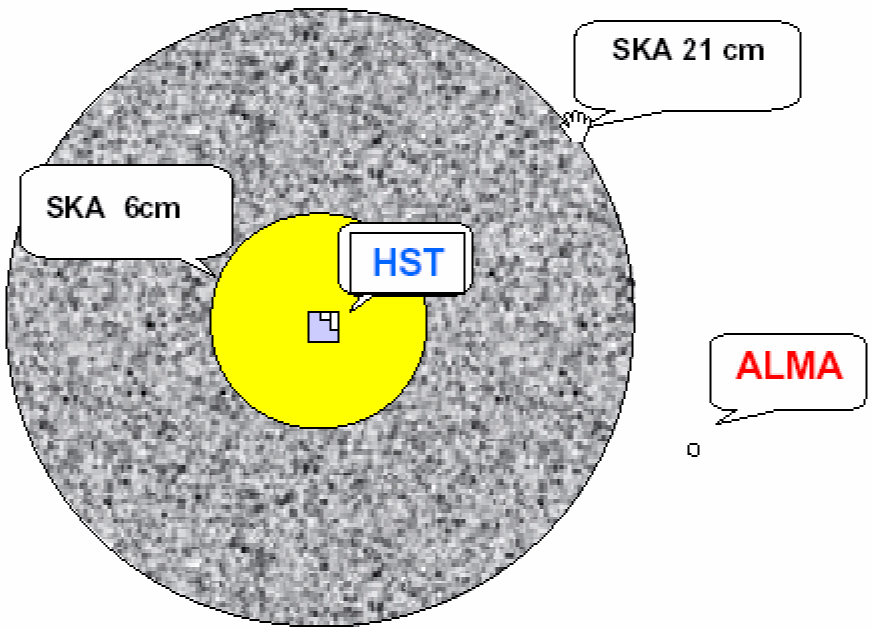




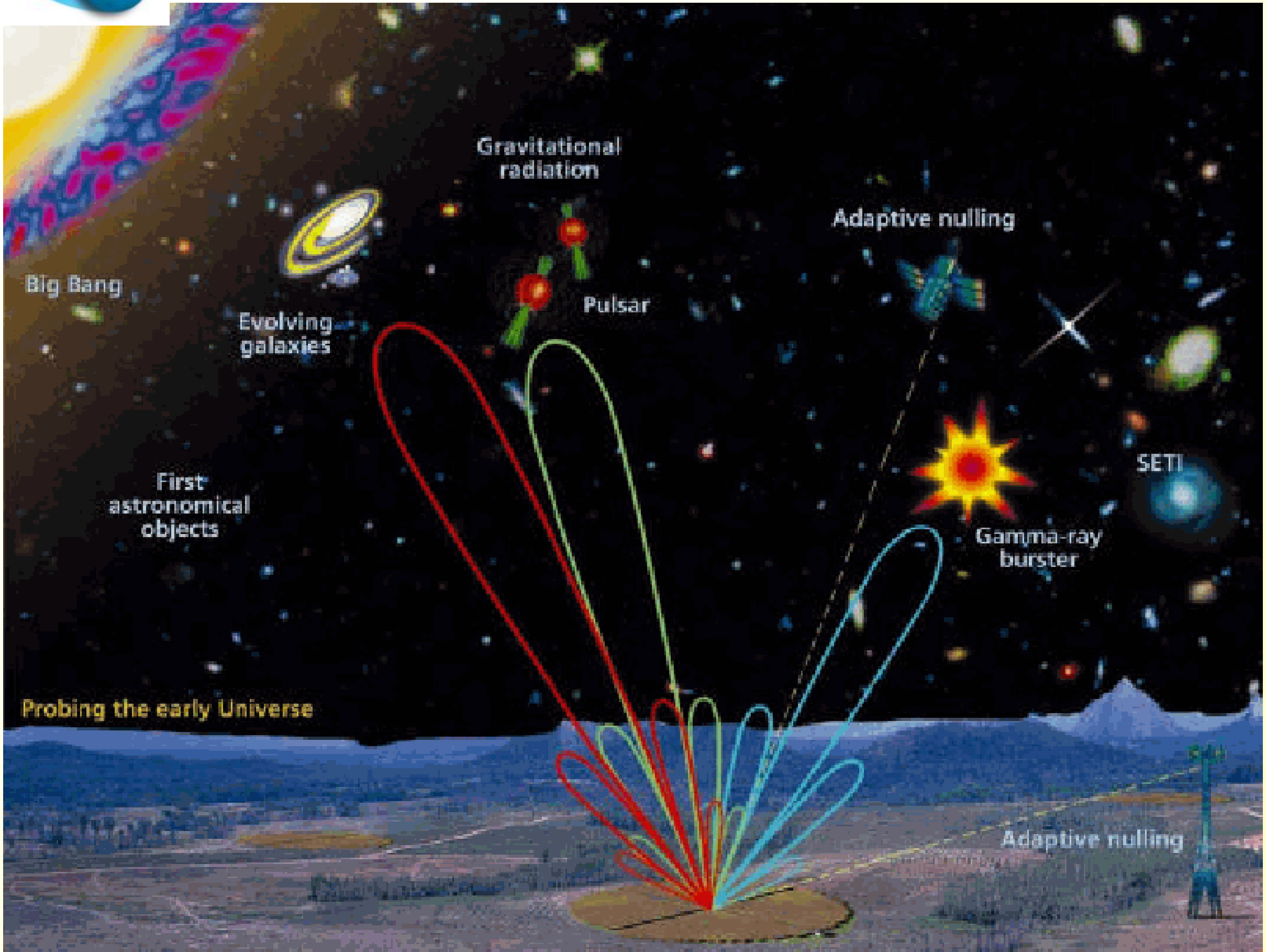
Field of View



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



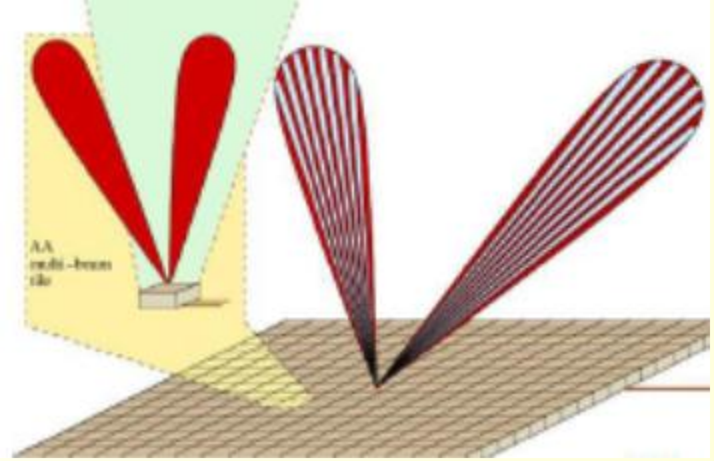
Multi-Beam

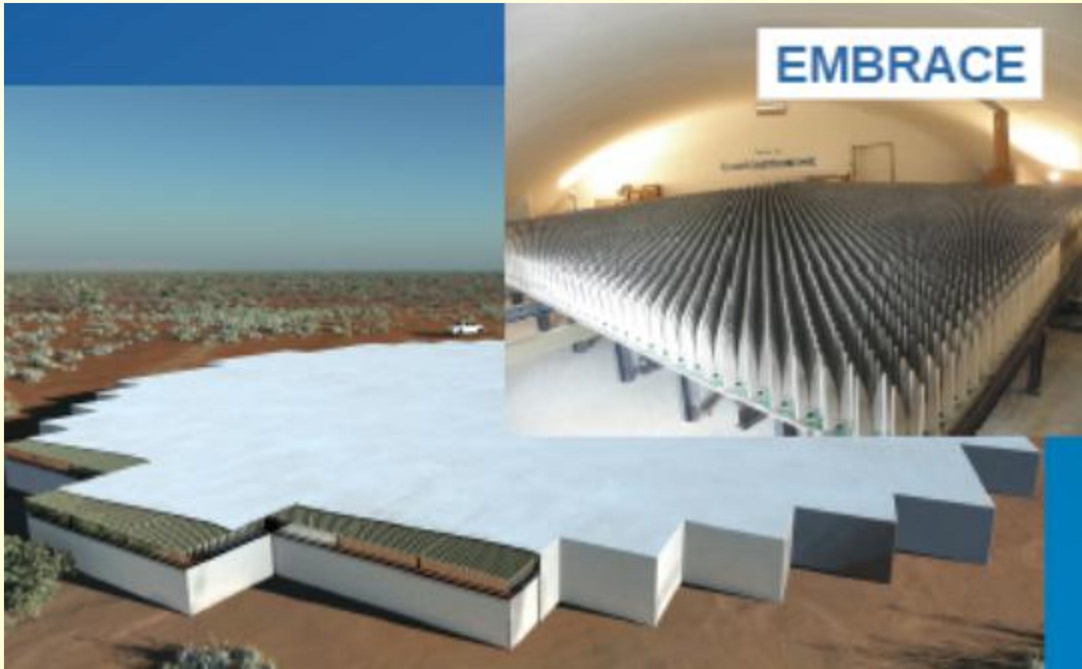

Gravitational radiation
Adaptive nulling
Big Bang
Evolving galaxies
Pulsar
First astronomical objects
SETI
Gamma-ray burster
Probing the early Universe
Adaptive nulling

New technology, new problems

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

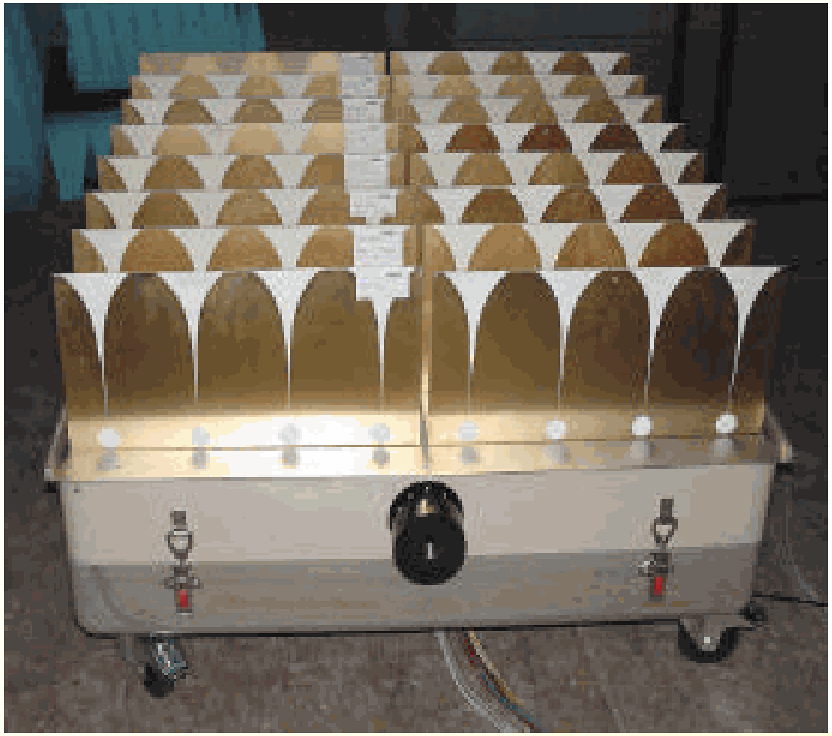
Low frequency: **EMBRACE** Beamforming

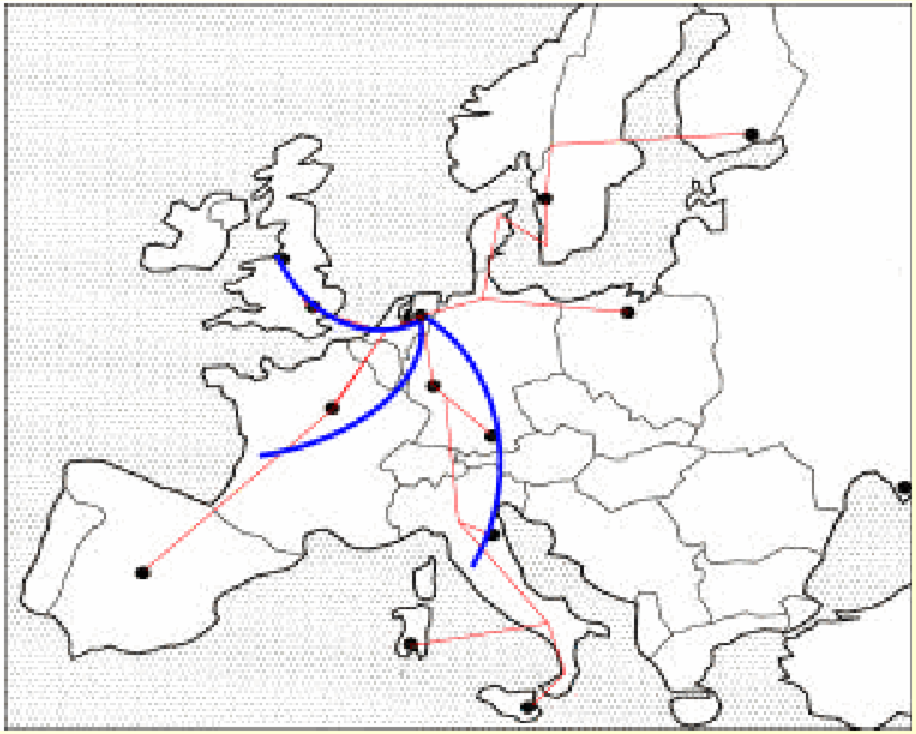




EMBRACE

Electronic MultiBeam Radio Astronomy ConcEpt





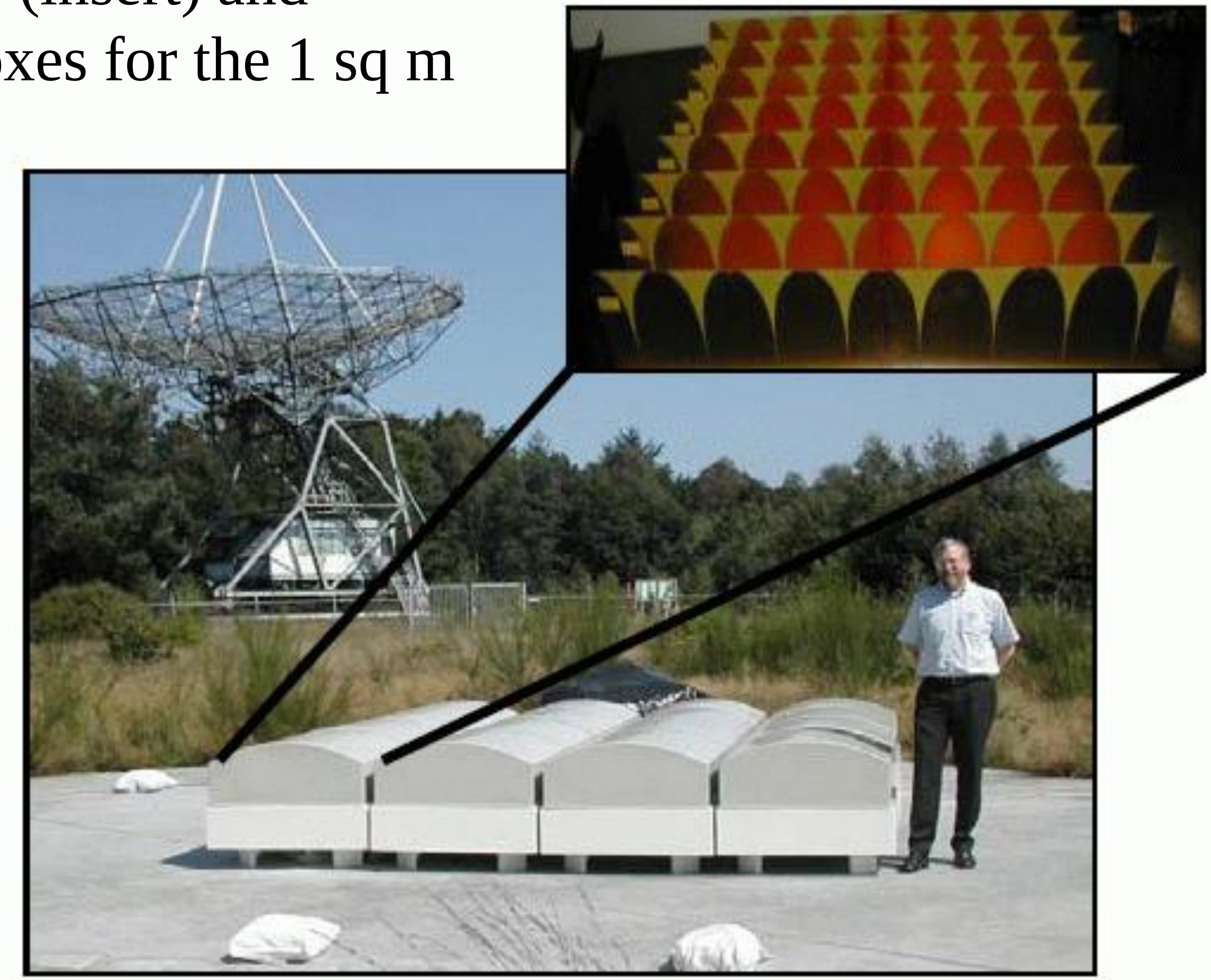
➔THEA array of 1 sq m, built at ASTRON

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

•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

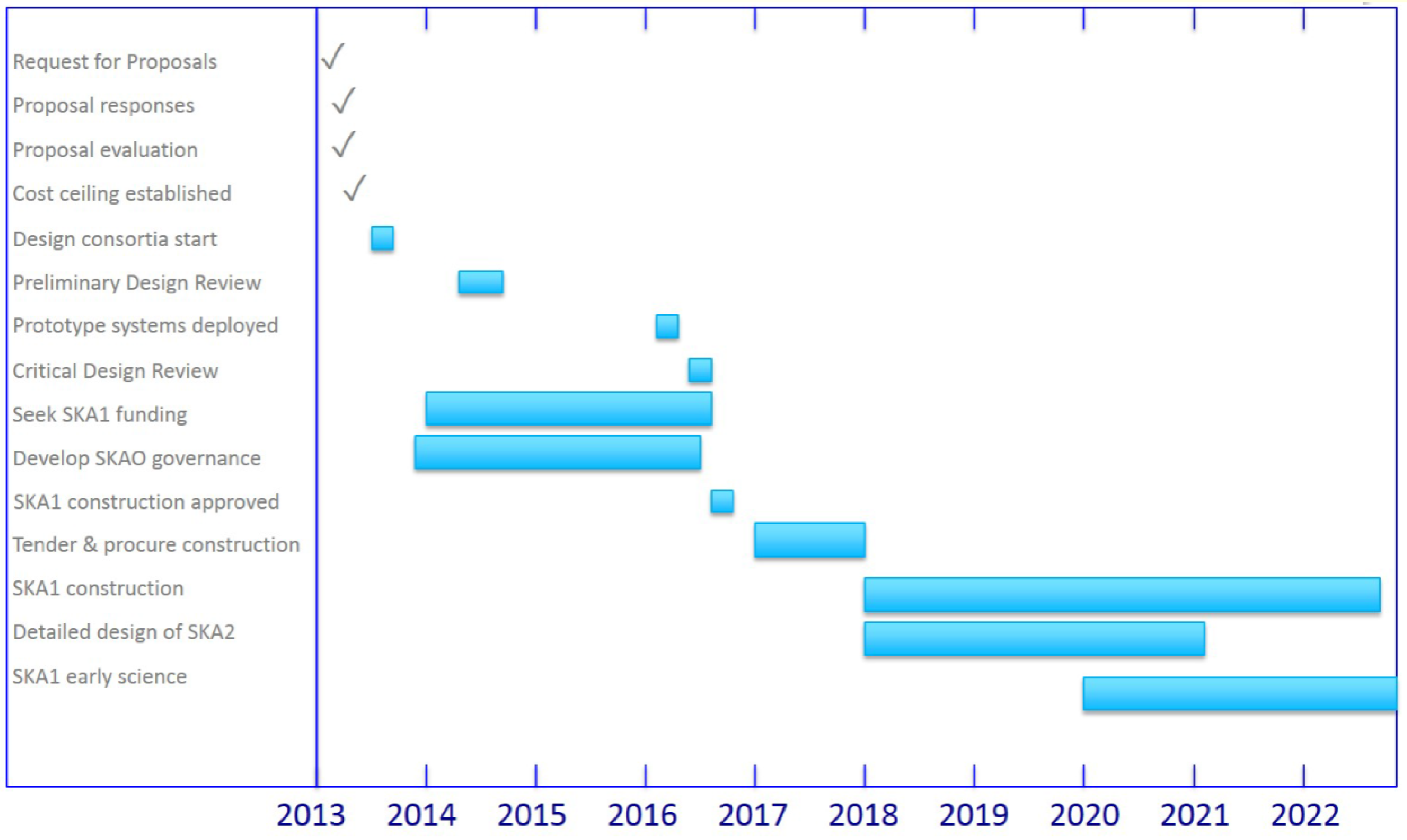
Terminology:

•SKA **Precursors**: the two radio telescopes being built on the two selected SKA sites
ASKAP 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.

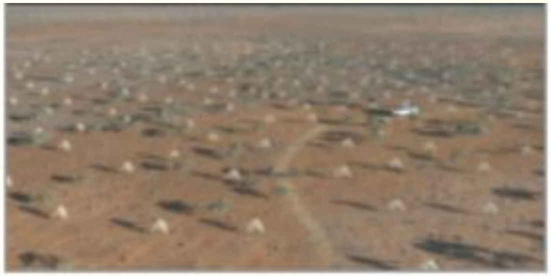


The SKA phases 1 & 2

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

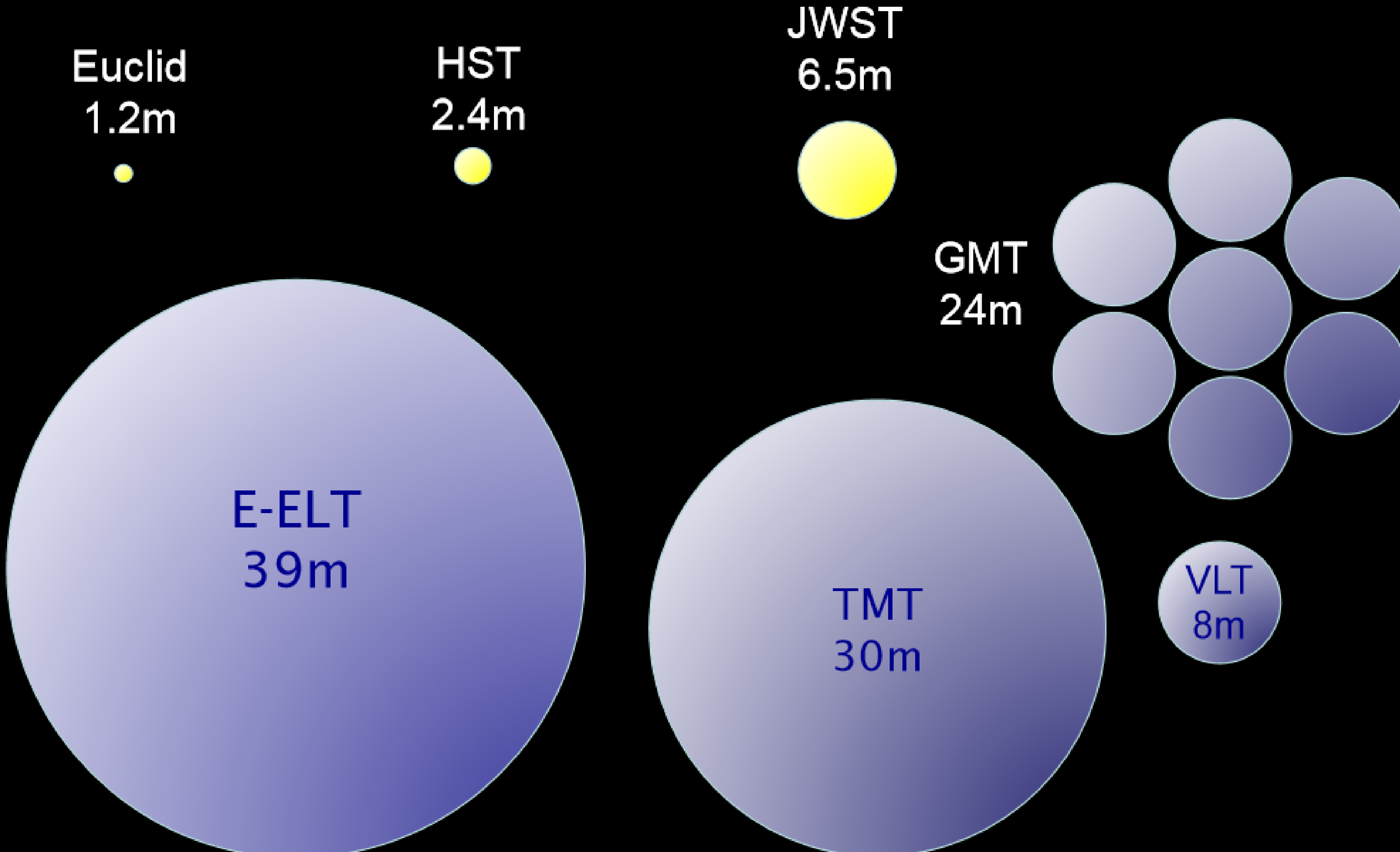
Australia

SKA2_MID
2500 Dishes

SKA2_AA
Mid Frequency Aperture Array Stations

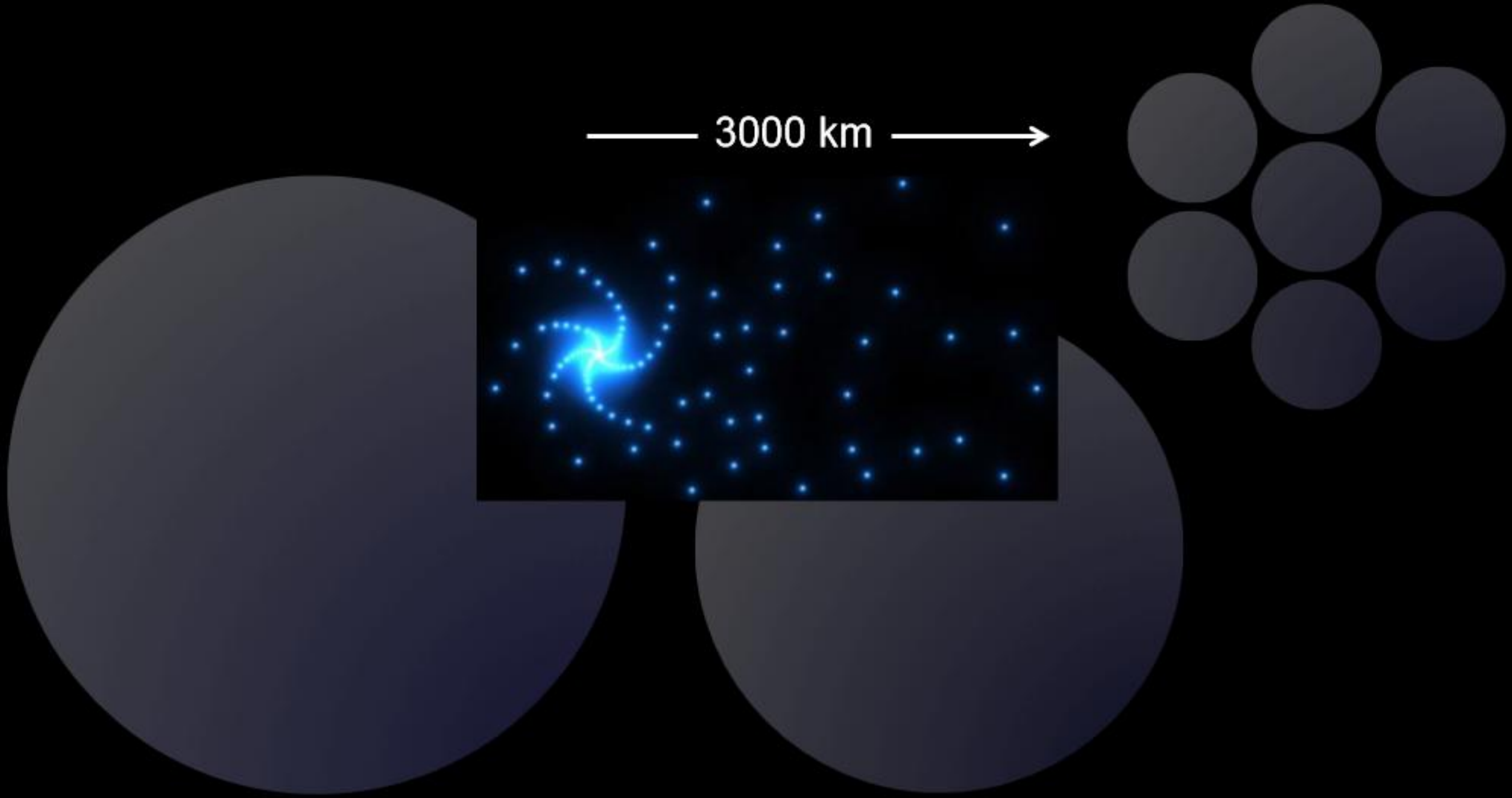
SKA2_LOW
Low Frequency Aperture Array Stations

Telescope primary mirrors



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

SKA footprint to scale /100,000



Two SKA Precursors

Frequency 0.7-1.8 GHz (HI at z=1)

ASKAP: Australia

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

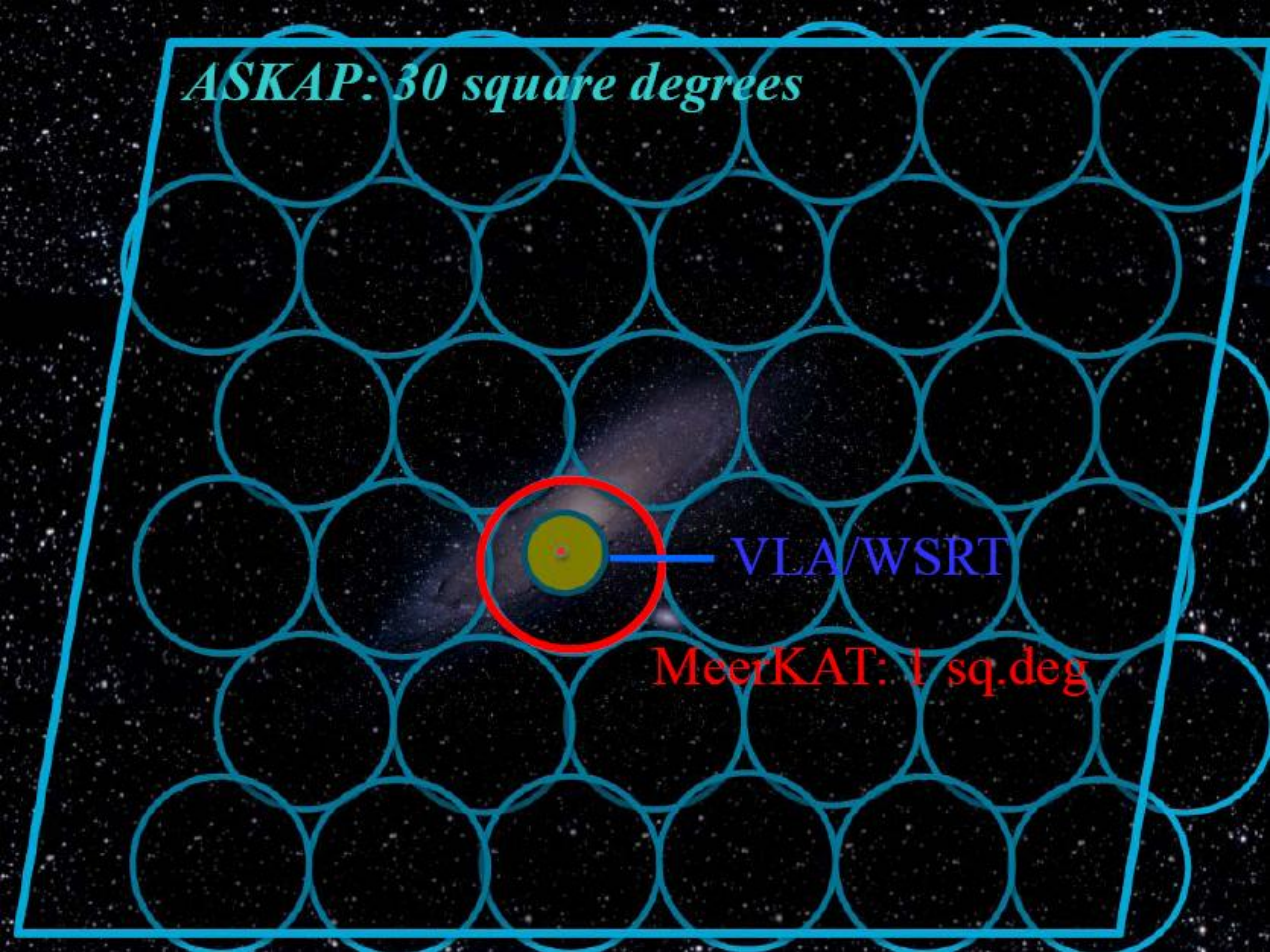
MEERKAT: South Africa

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 early 2016

ASKAP

MeerKAT


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

SKA precursor Complementarity

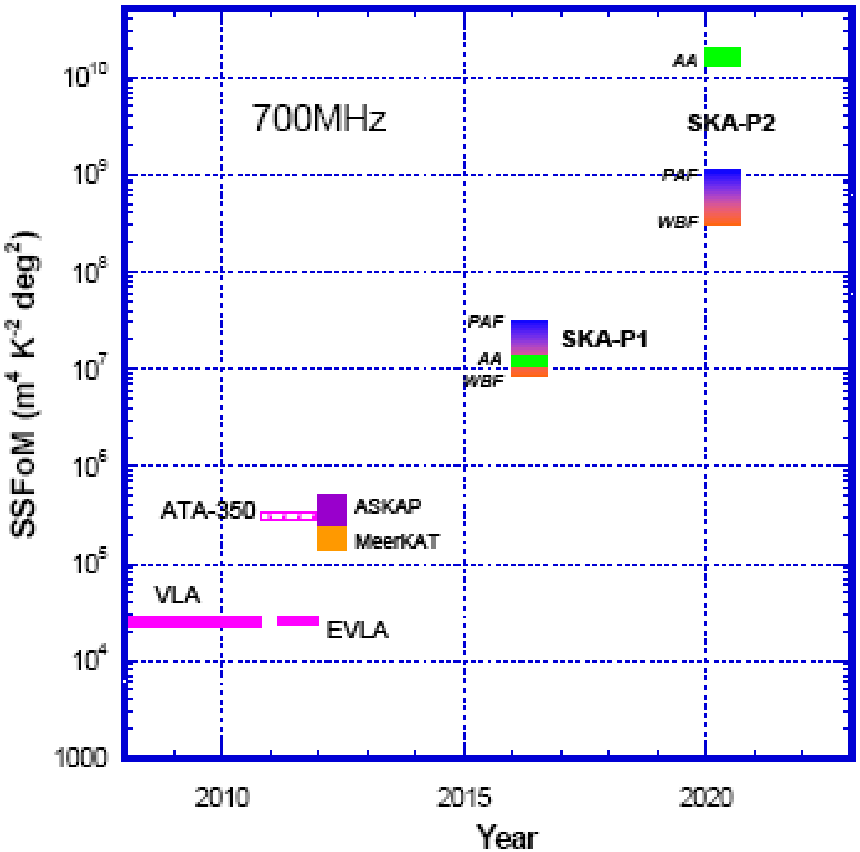
ASKAP:
-large fields/all-sky, relatively shallow surveys

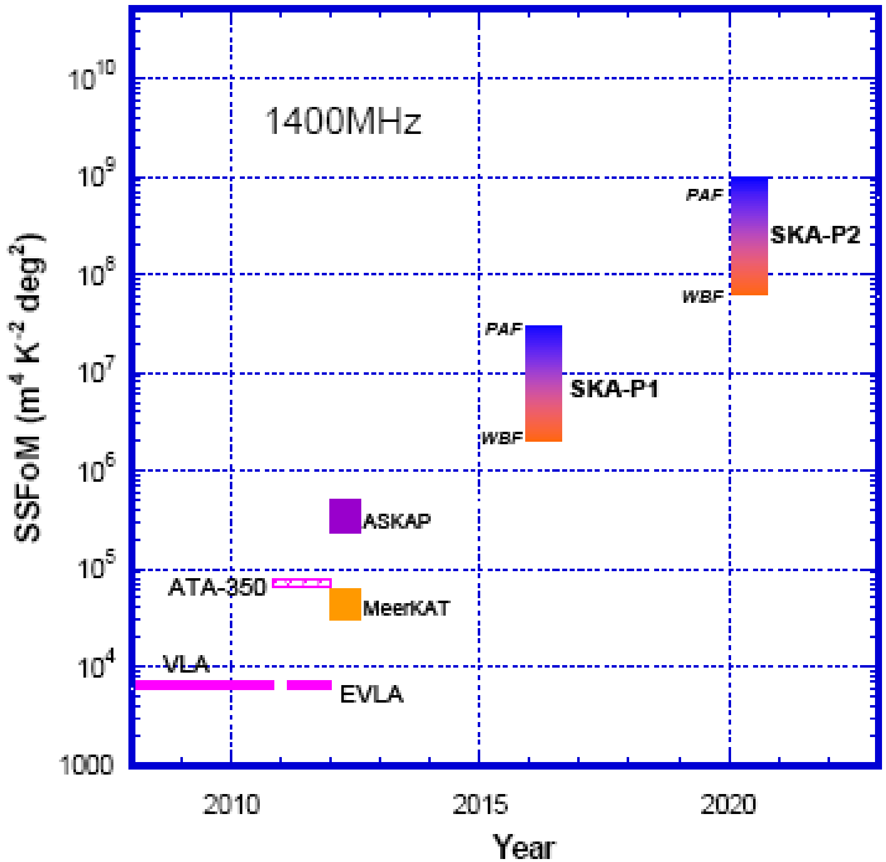
MeerKAT
-smaller fields, deeper surveys, higher/lower resolution

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

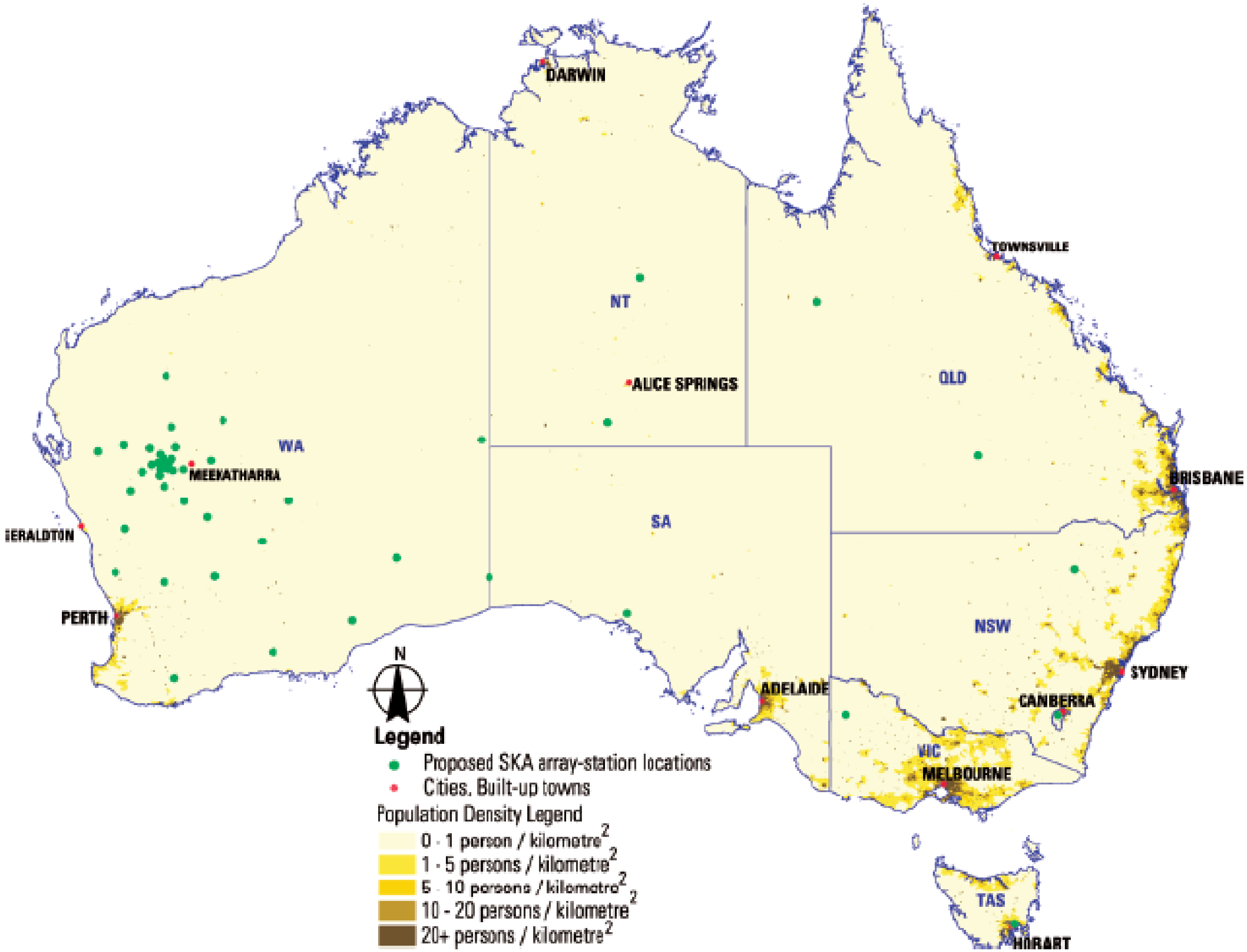
VLA:
-deep integration of small fields, down to δ-40 °only

SKA survey speeds



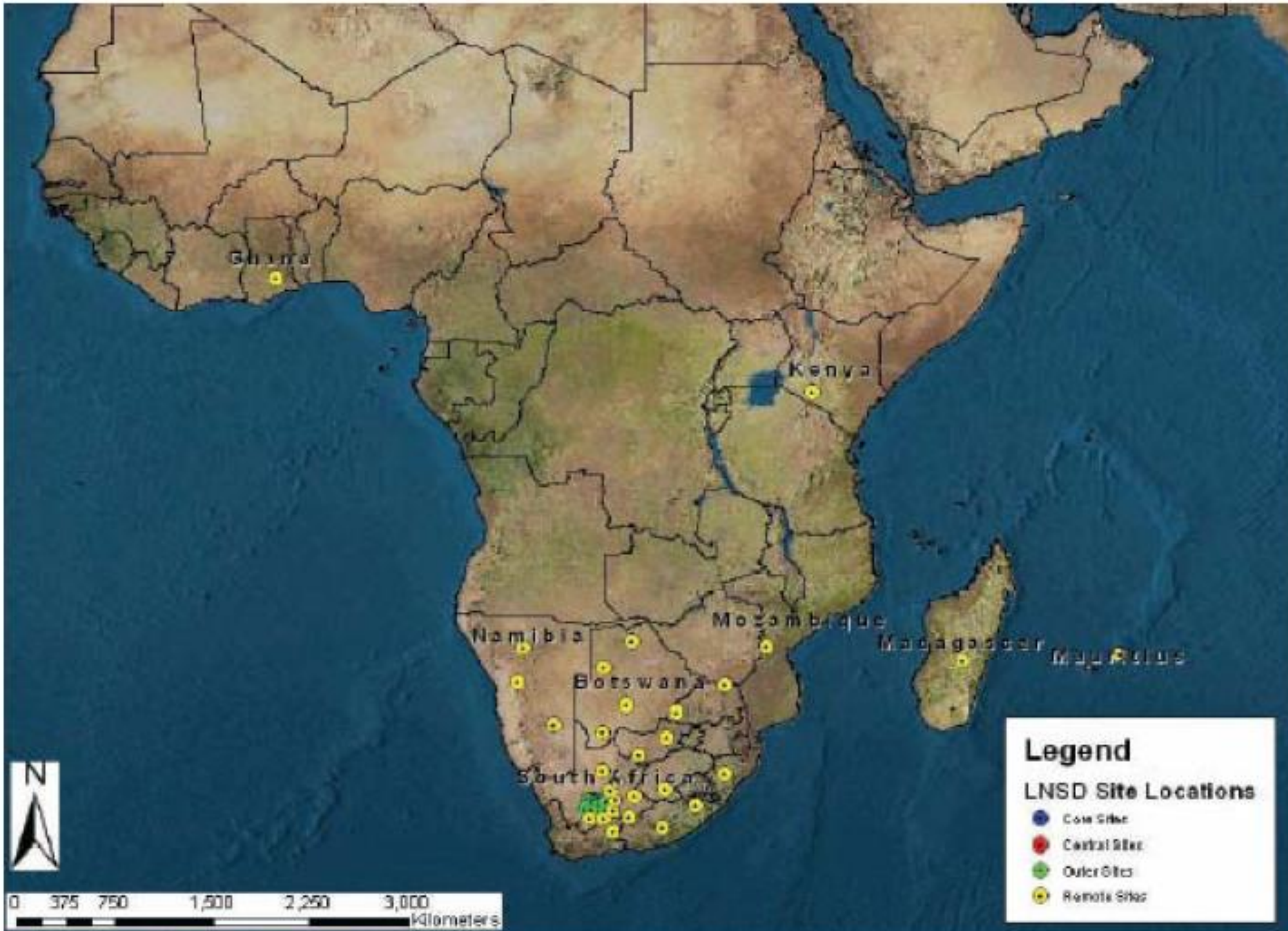


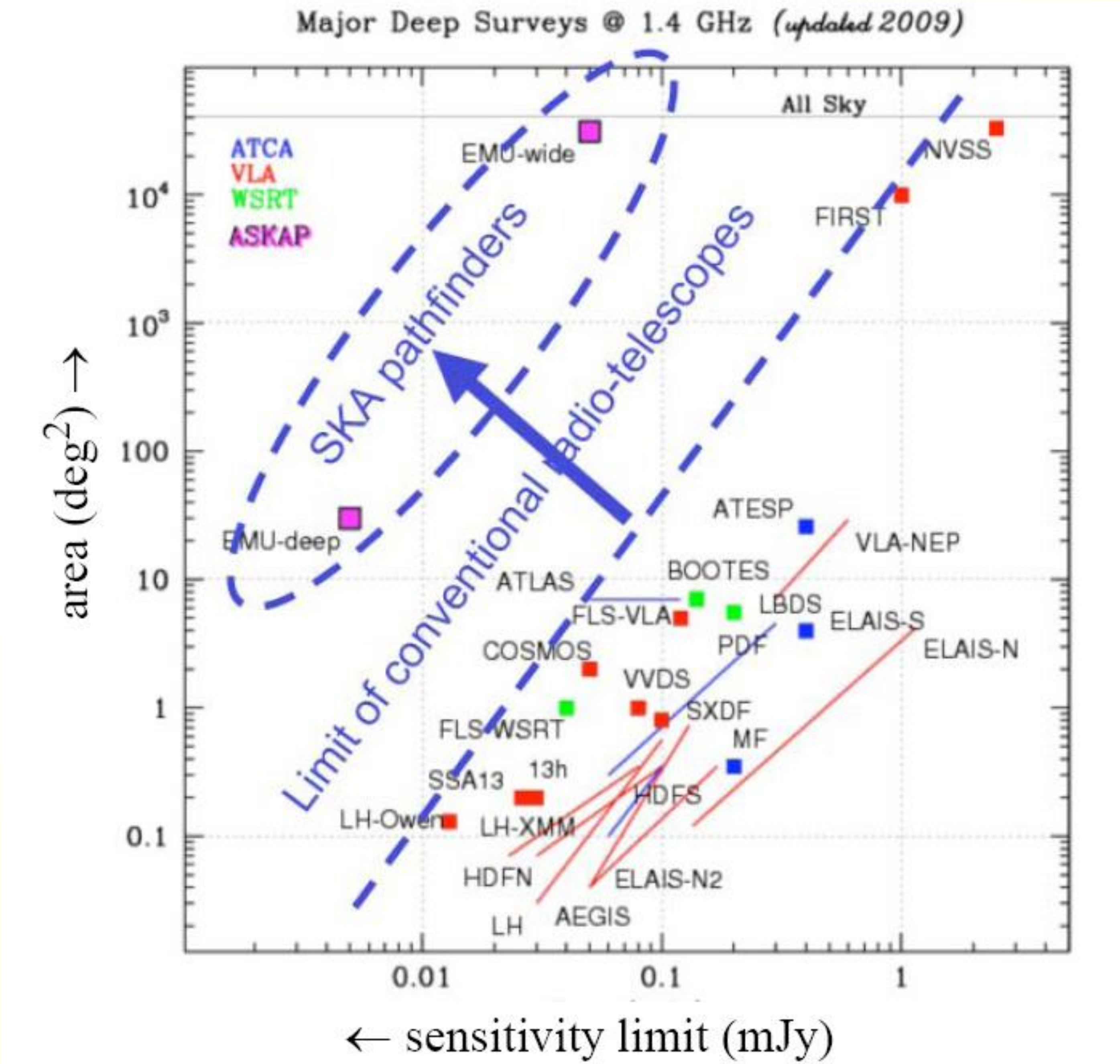
Australia



DARWIN
NT
ALICE SPRINGS
QLD
TOWNSVILLE
BRISBANE
WA
MEEKATHARRA
GERALDTON
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
13h
SSA13
HDFS
LH-Owen
LH-XMM
HDFN
ELAIS-N2
LH
AEGIS
area (deg²) →
← sensitivity limit (mJy)
10⁴
10³
100
10
1
0.1
0.01
0.1
1

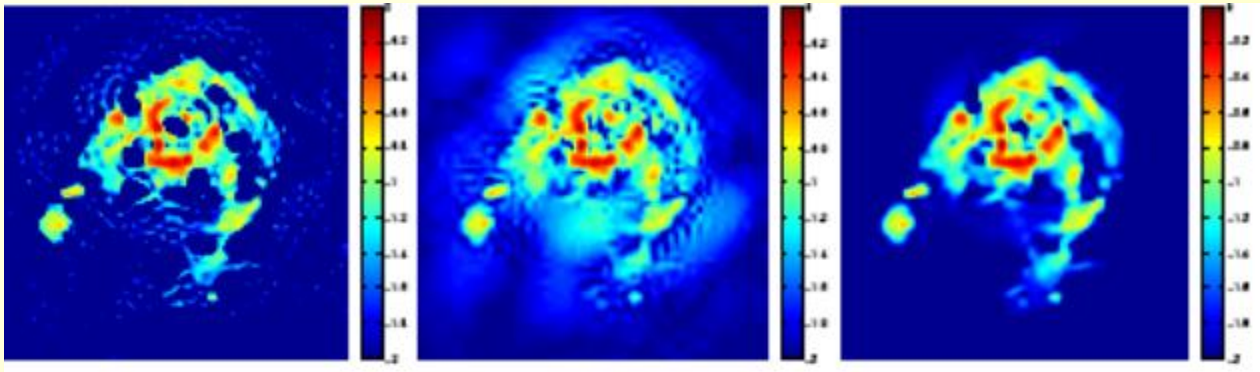
Data management

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

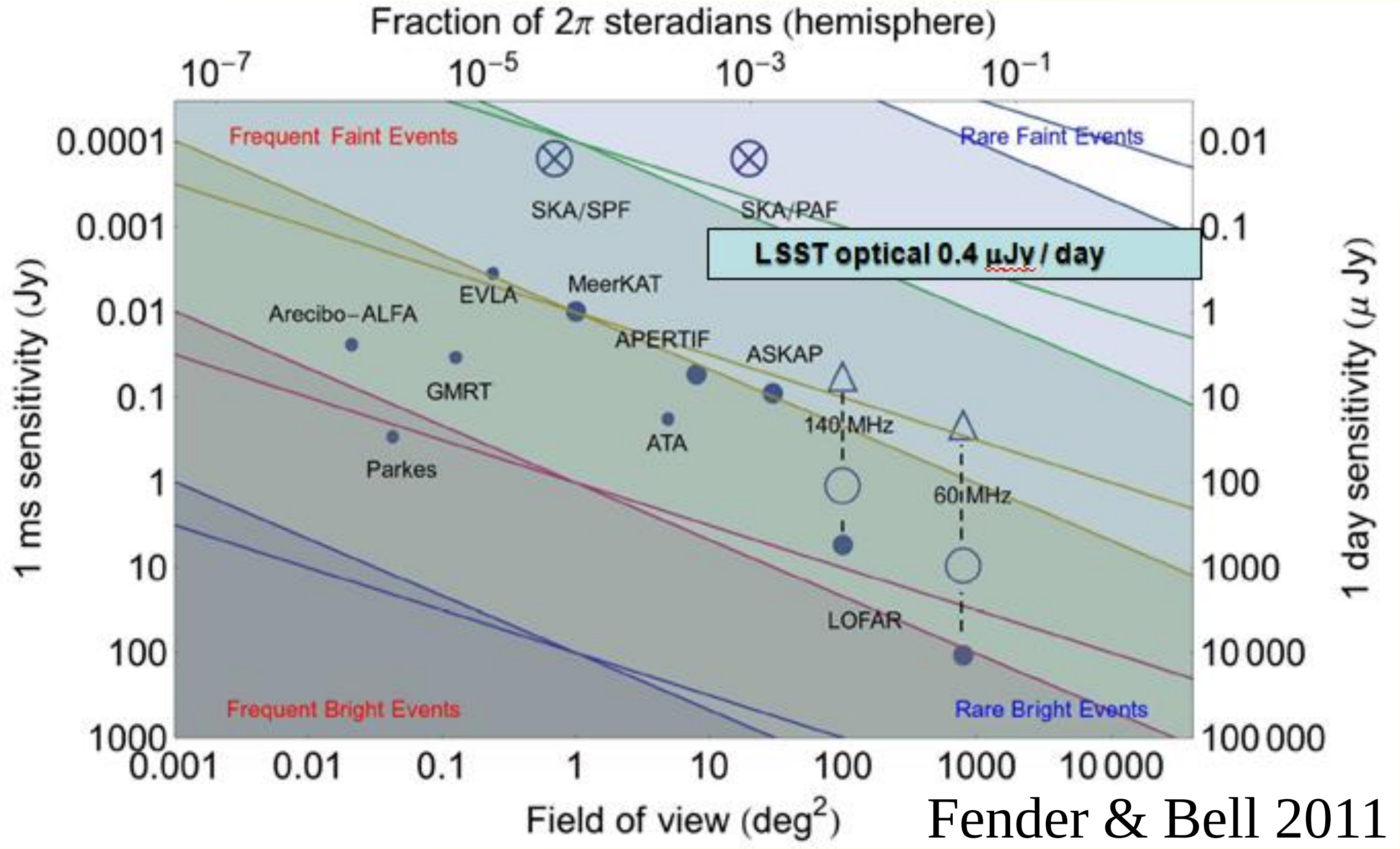


(c) "CLEAN"   (d) "MS-CLEAN"   (e) SARA

A new dimension: the transient sky

4 FRB found , 5 FRB per day expected with SKA2

LSST (Large Synoptic Telescope) millions of alerts/day



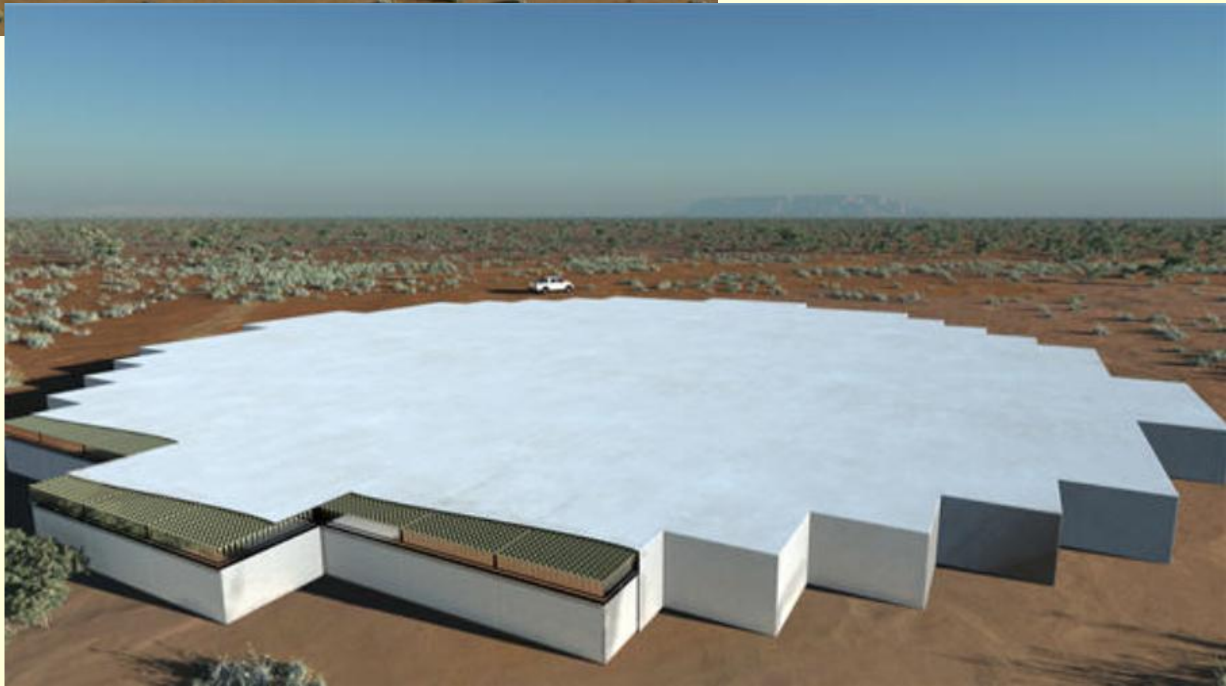
Fender & Bell 2011

PopIII SN?

Dishes

High frequency (South Africa)

Mid Frequency



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