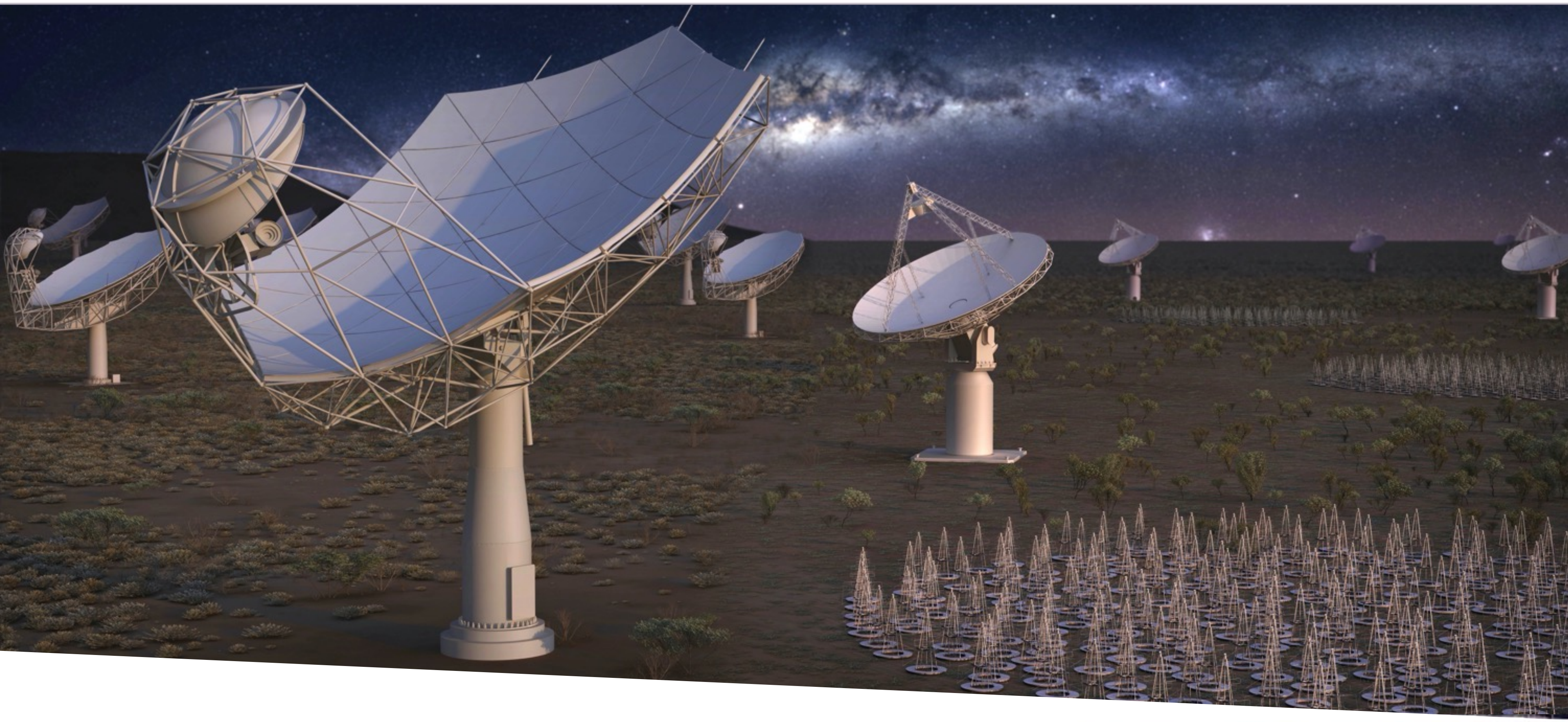
ASTRONOMY in the NEXT DECADES with SKAO



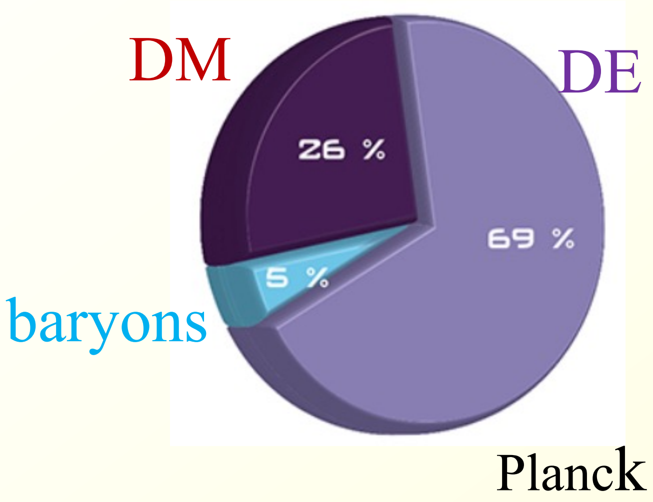
SQUARE KILOMETRE ARRAY

Exploring the Universe with the world's largest radio telescope

Françoise Combes
Observatoire de Paris

November 2022

SKA: key science

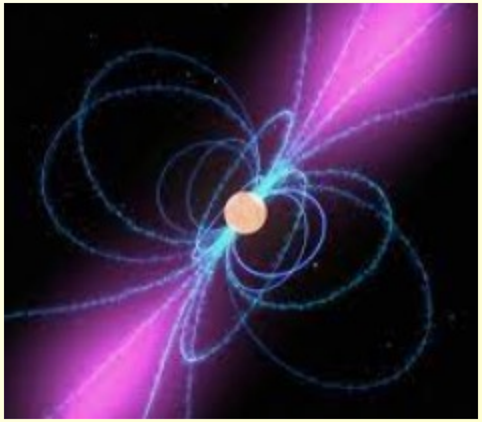


Dark energy: (BAO, WL, RSD..)
Is it varying with time?

Matter in the Universe Dark matter vs z

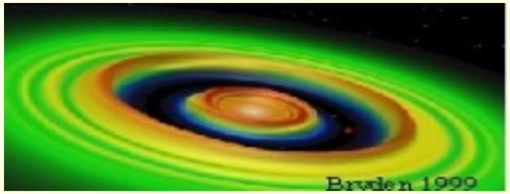
How is the Universe re-ionized?
End of the dark age: cosmic dawn, EoR

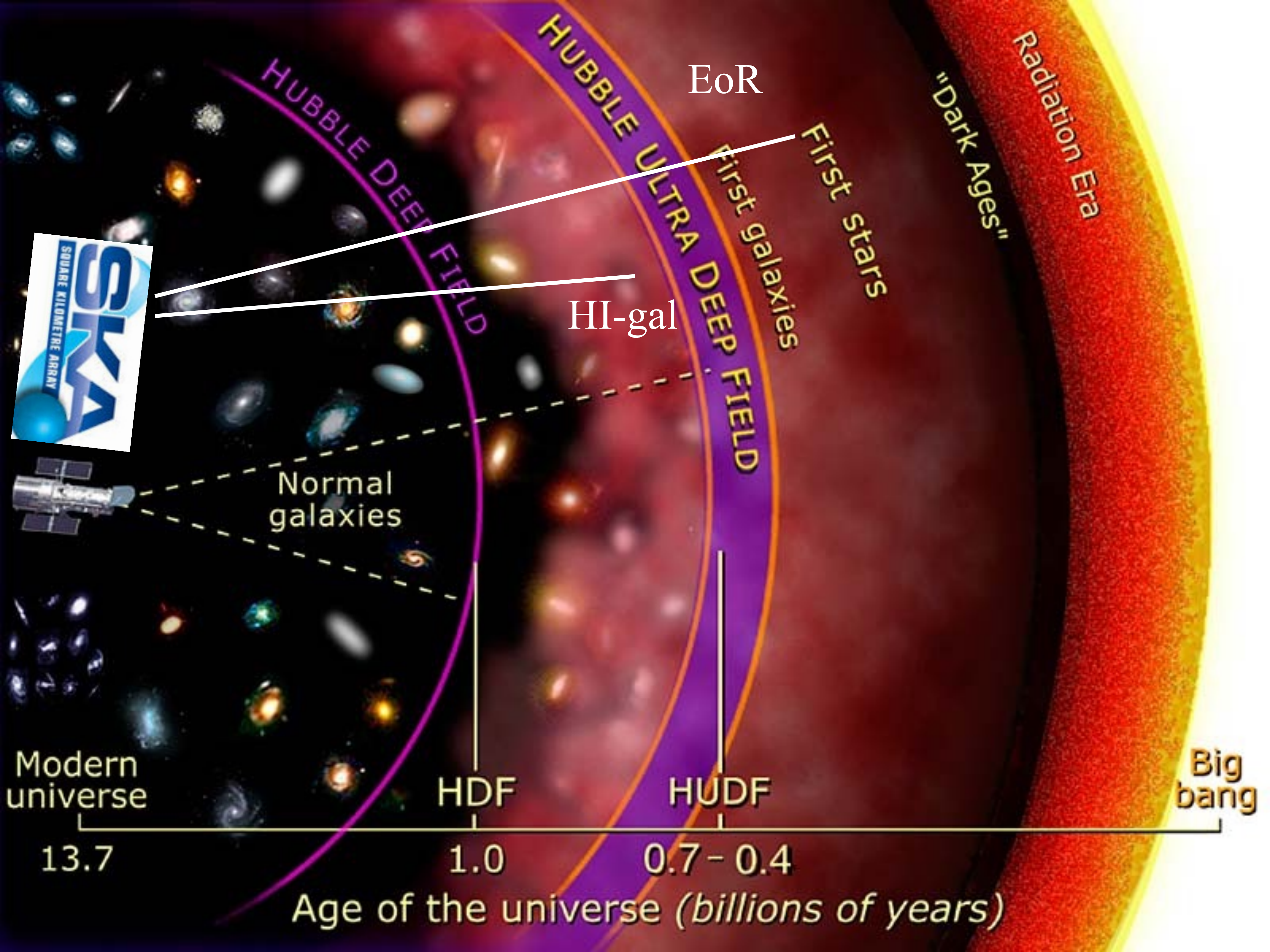
How do baryons assemble into the large-scale structures?
Galaxy formation and evolution



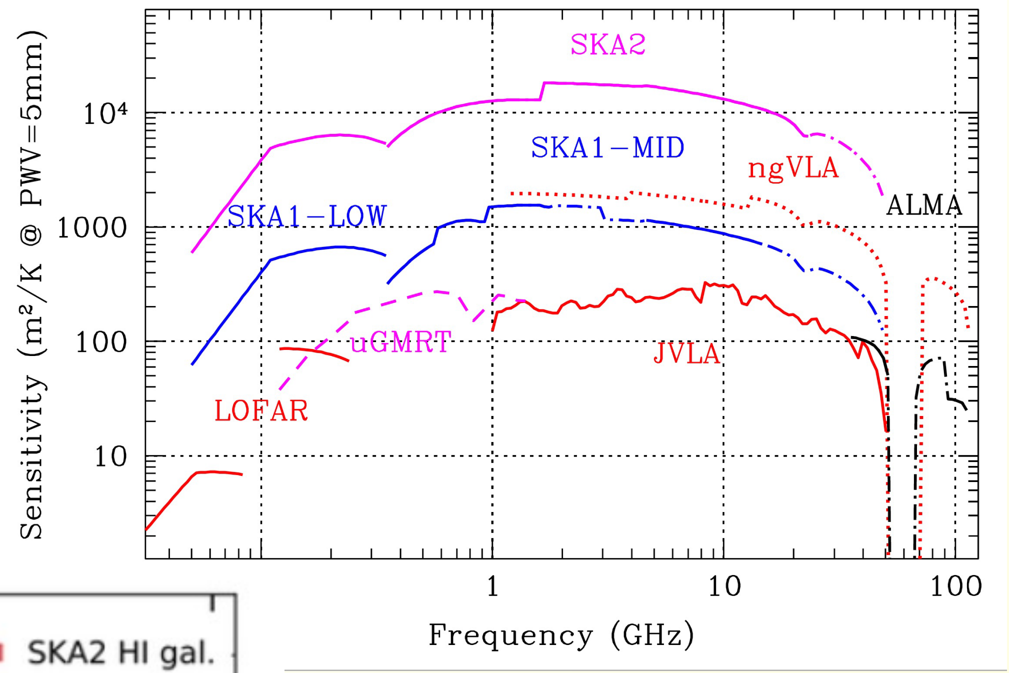
Strong-gravity with pulsars and black holes

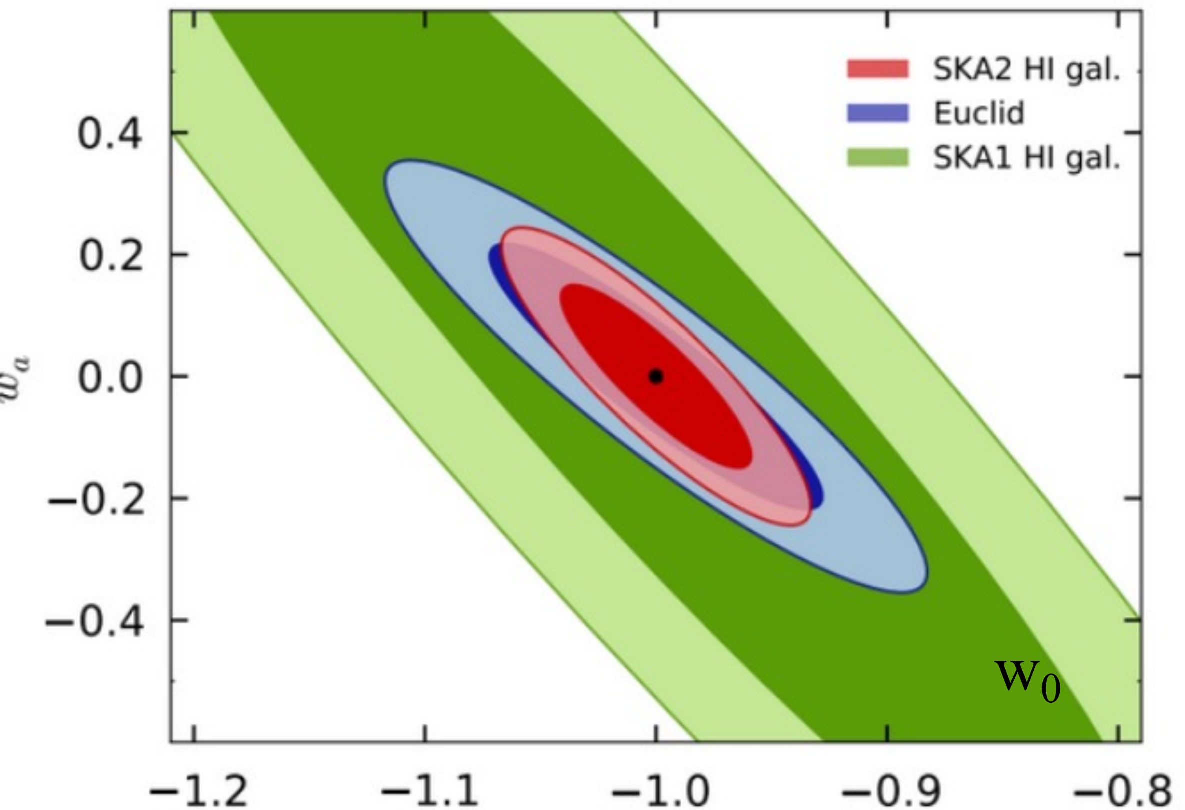
Cosmic magnetism
Craddle of life




EoR
First stars
First galaxies
"Dark Ages"
Radiation Era
HUBBLE DEEP FIELD
HUBBLE ULTRA DEEP FIELD
HI-gal
SKA
SQUARE KILOMETRE ARRAY
Normal galaxies
Modern universe
HDF
HUDF
Big bang
13.7
1.0
0.7 – 0.4
Age of the universe (billions of years)

Constraints on DE with HI gal survey



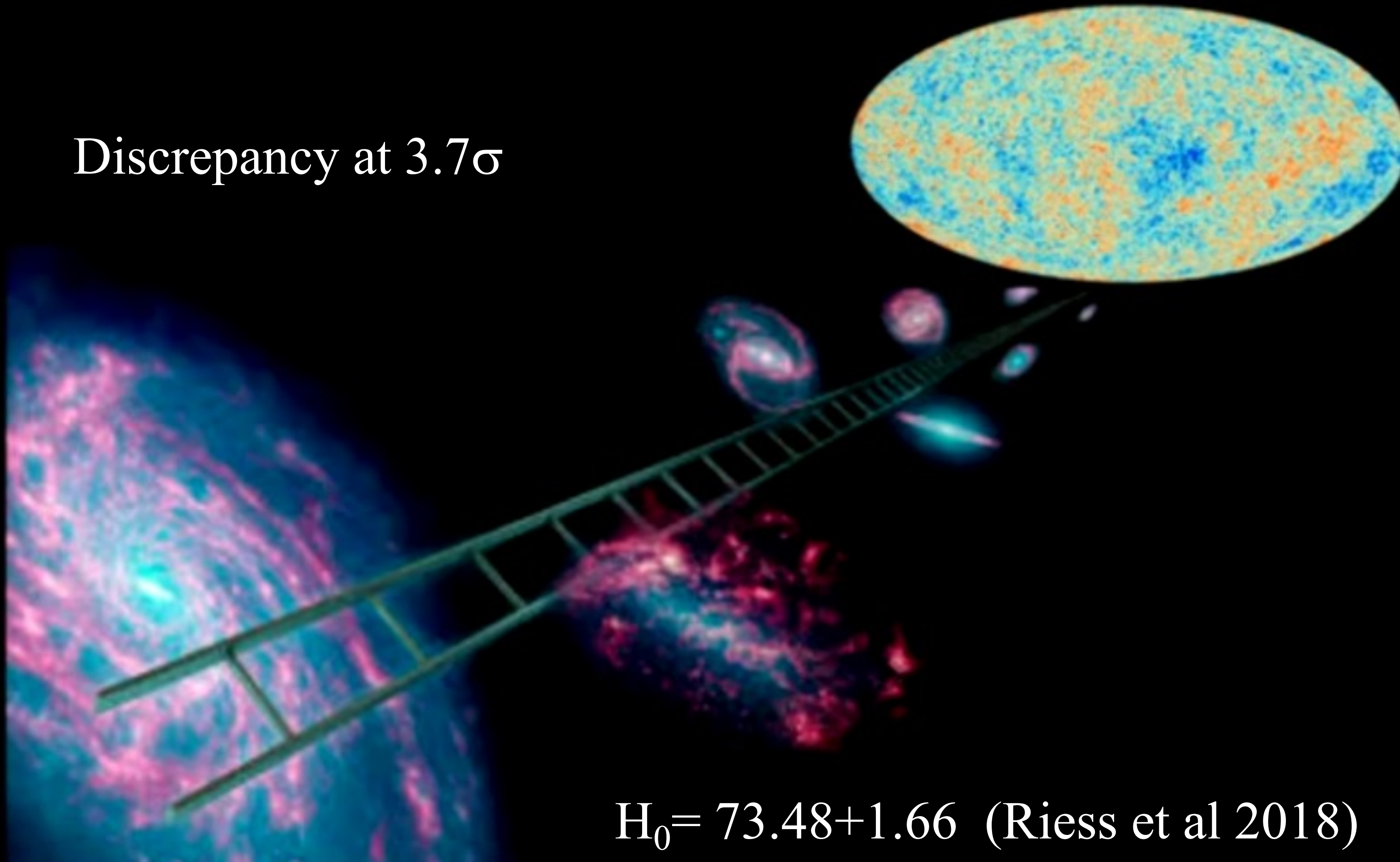


SKAO

H_0= 67.8+0.9 (Planck coll 2016)

The H_0 challenge

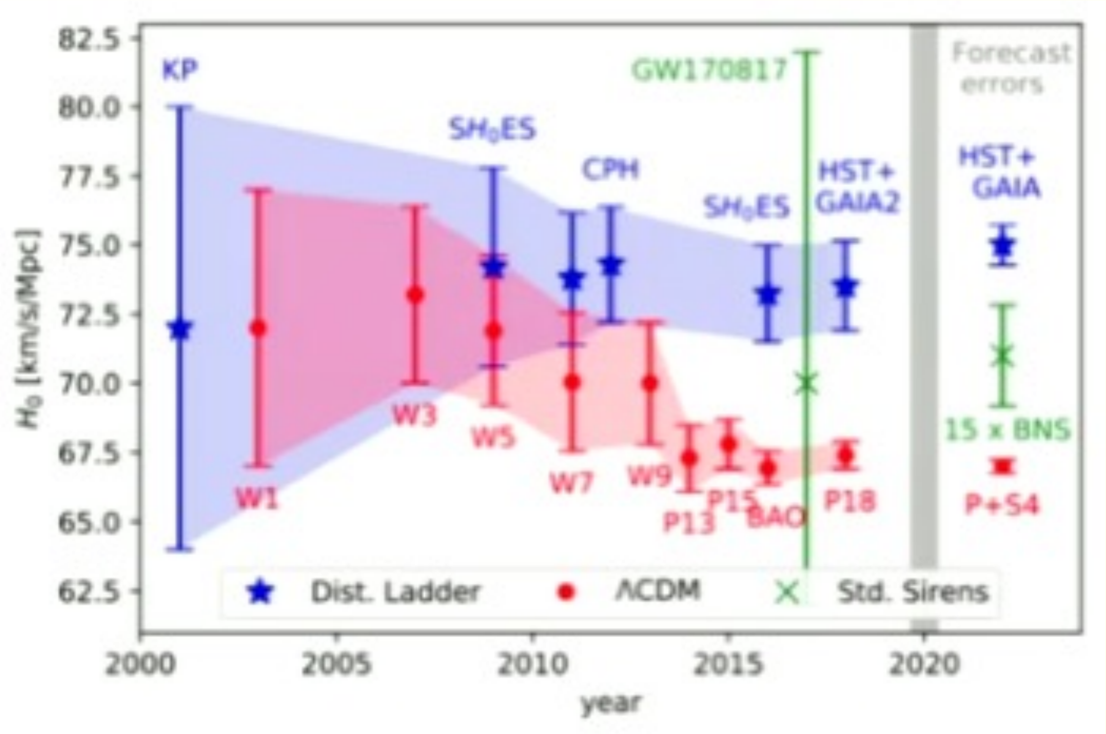
Discrepancy at 3.7σ

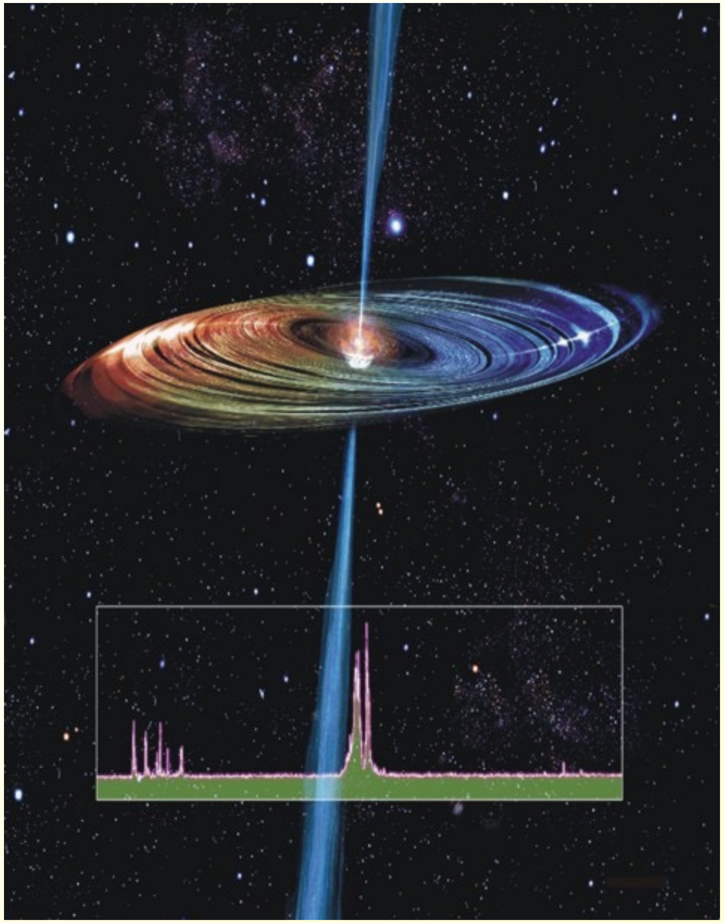


H_0= 73.48+1.66 (Riess et al 2018)

Precise and accurate measure of H0

SKA will measure many masers around AGN at various z





Ezquiaga 2018

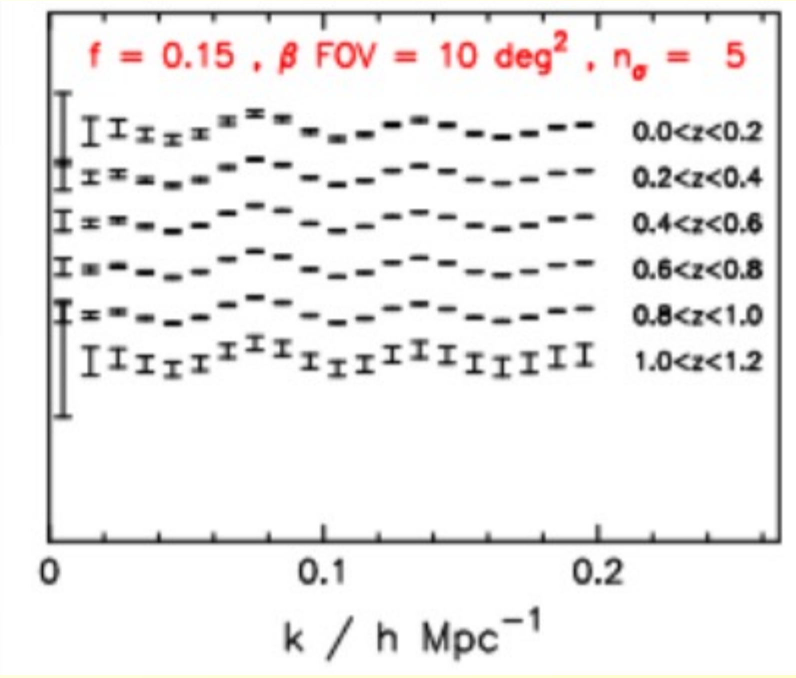
HI surveys for BAO with SKA-1

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

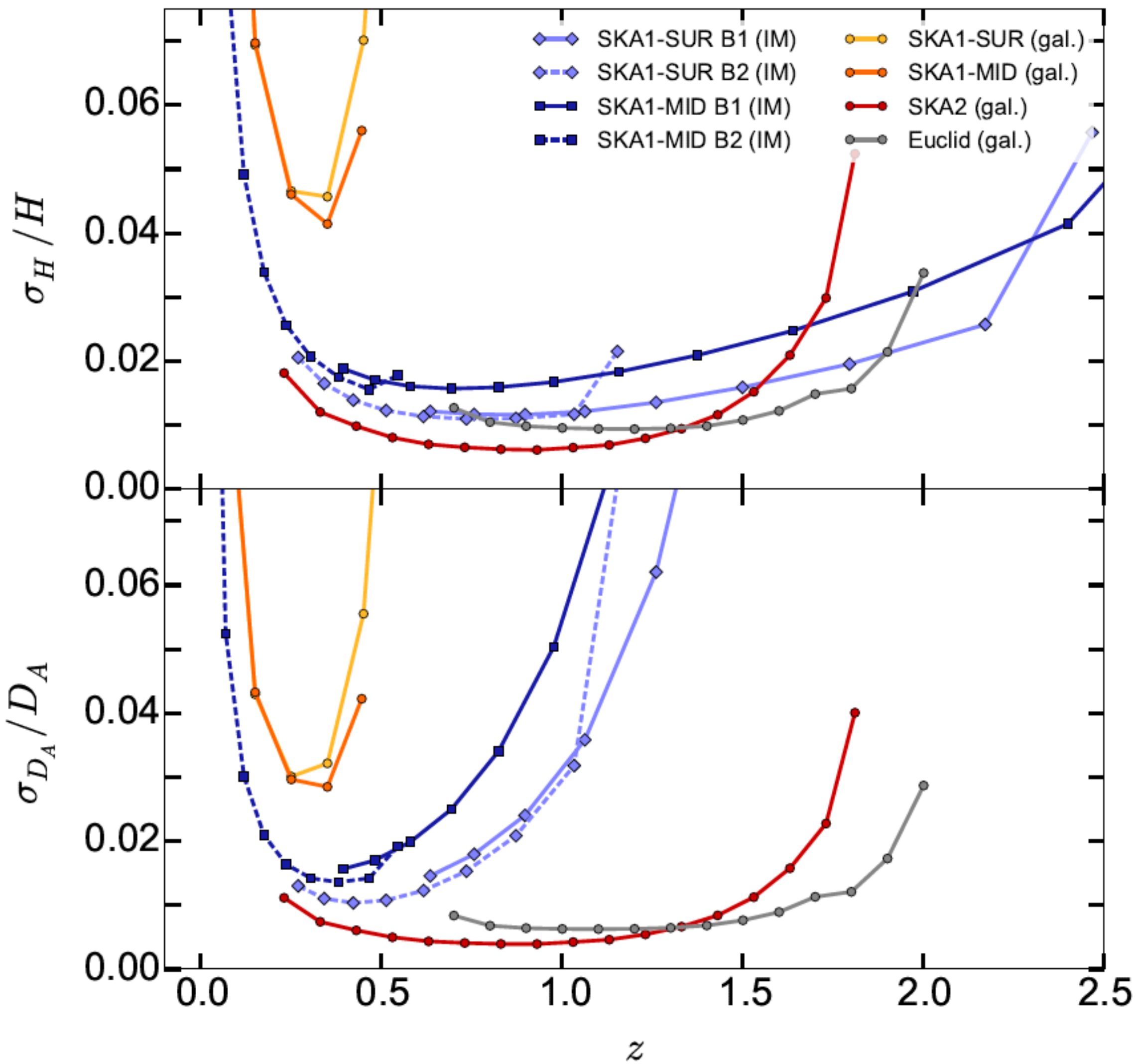
More competitive: HI intensity mapping 30 000 deg^2 up to z=3
Deep and wide, large volumes, ~Euclid

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

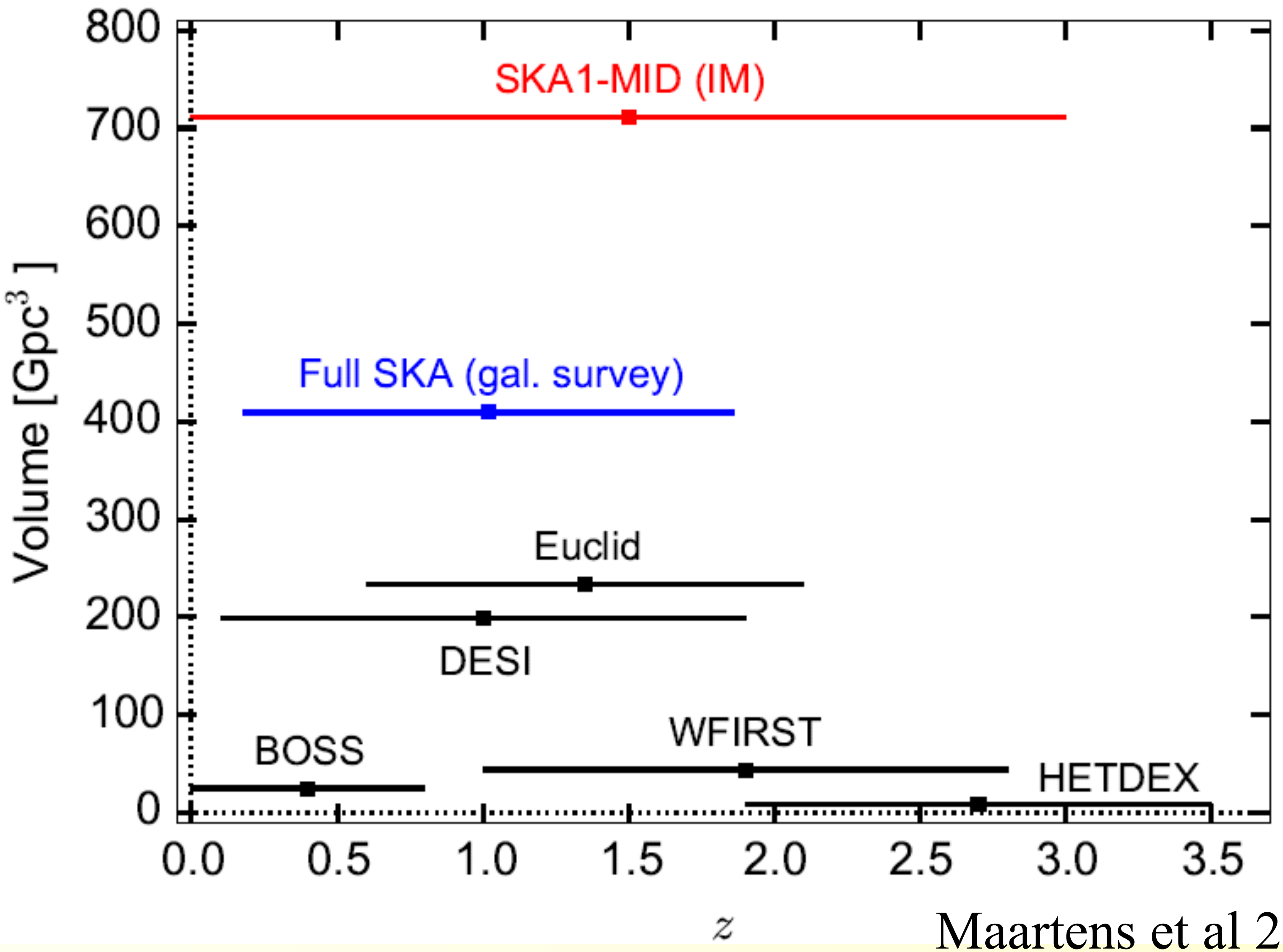
B1 low-frequency band
B2 high-frequency band

HIM 30 000 °2
up to z~3,
Radio 30 000 °2
up to z~6

10^9 objects

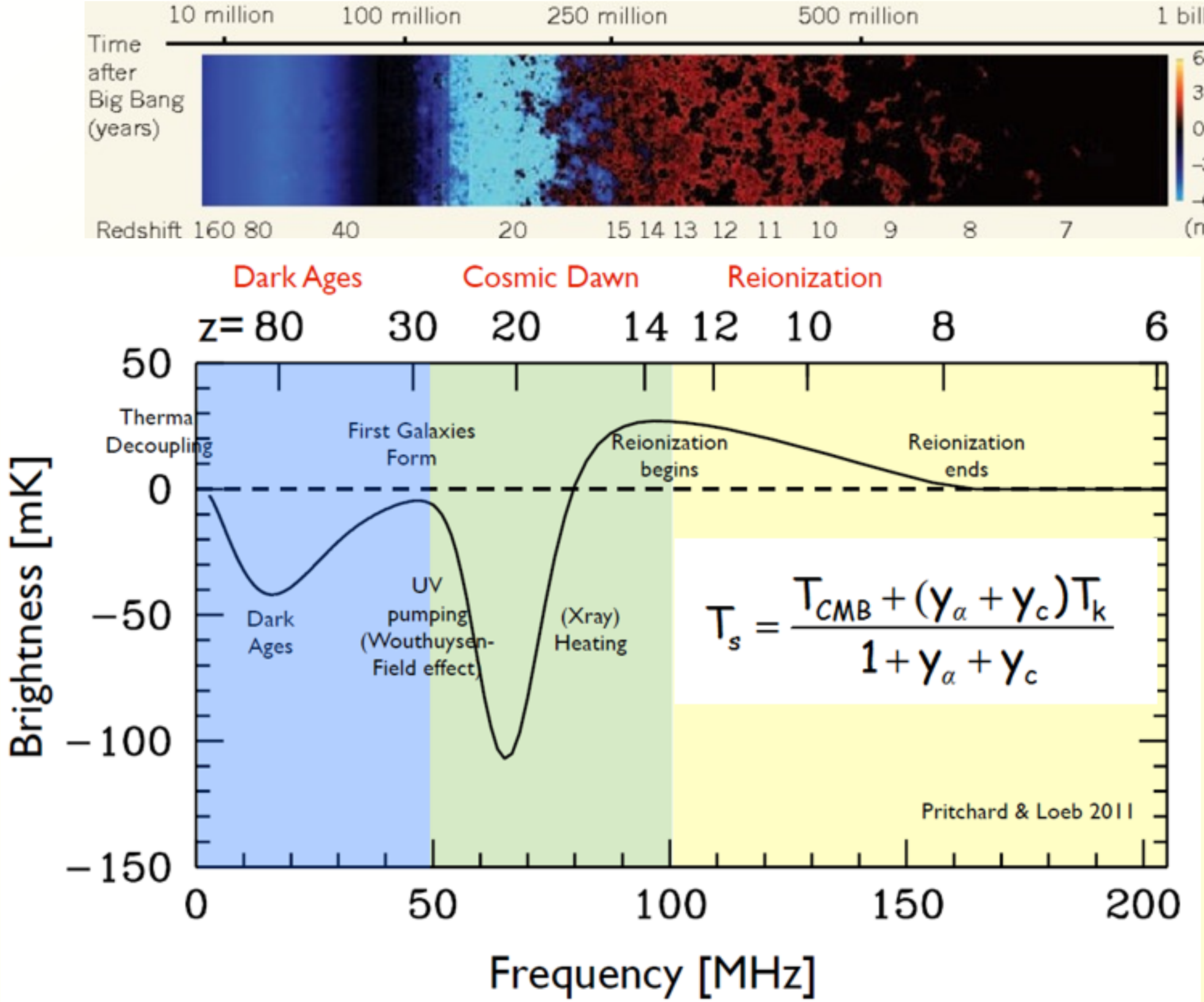
Maartens et al 2015

Comparison of Volume covered

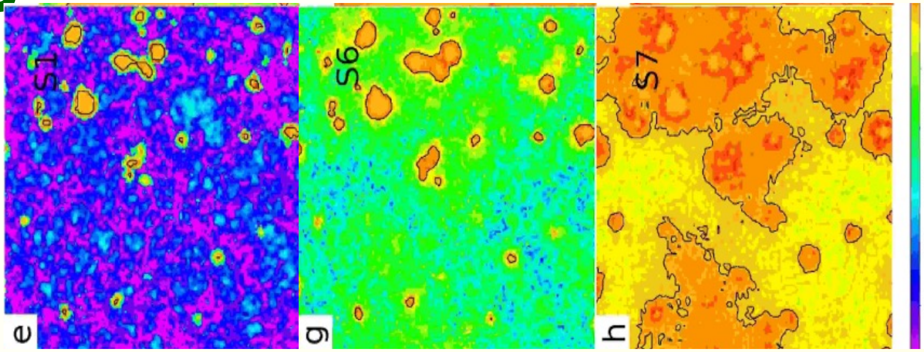


Maartens et al 2015

EoR: Epoch of reionization



Reionization- Primordial galaxies
SKA- JWST- ALMA



Stars   Stars +QSO   Stars + more QSO

(1) High-z **quasars**: Lyα emission (absorption, meadow & forest)

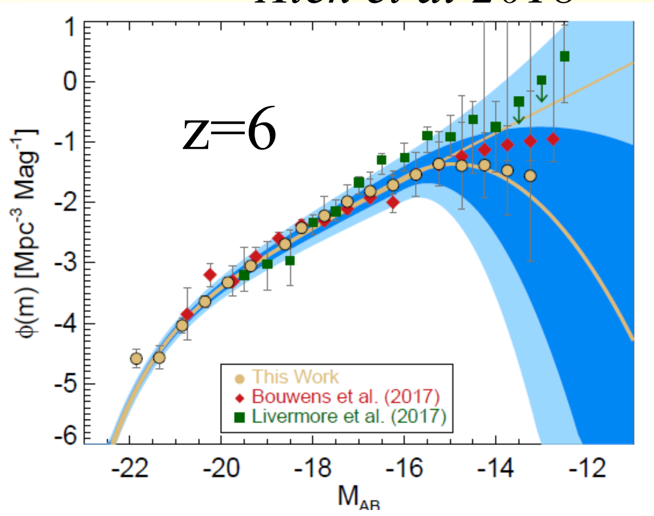
(2) Lyman break technique **(LBG)** luminosity function versus z

(3) Lyα emitters, **LAE**

(4) ALMA: **CO, [CII] lines**

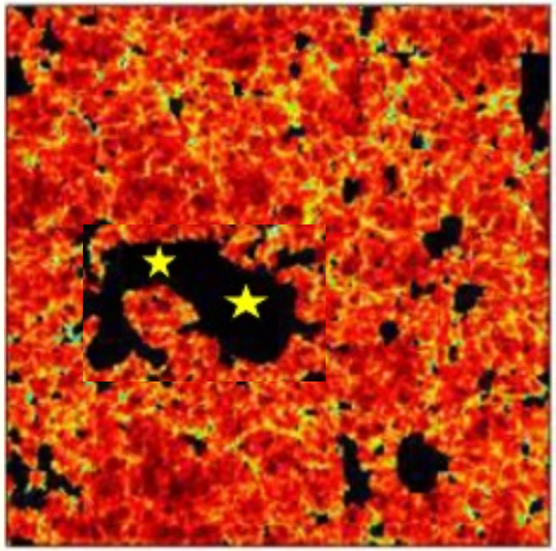
➔ **At high z: gravitationnal lenses**

Atek et al 2018



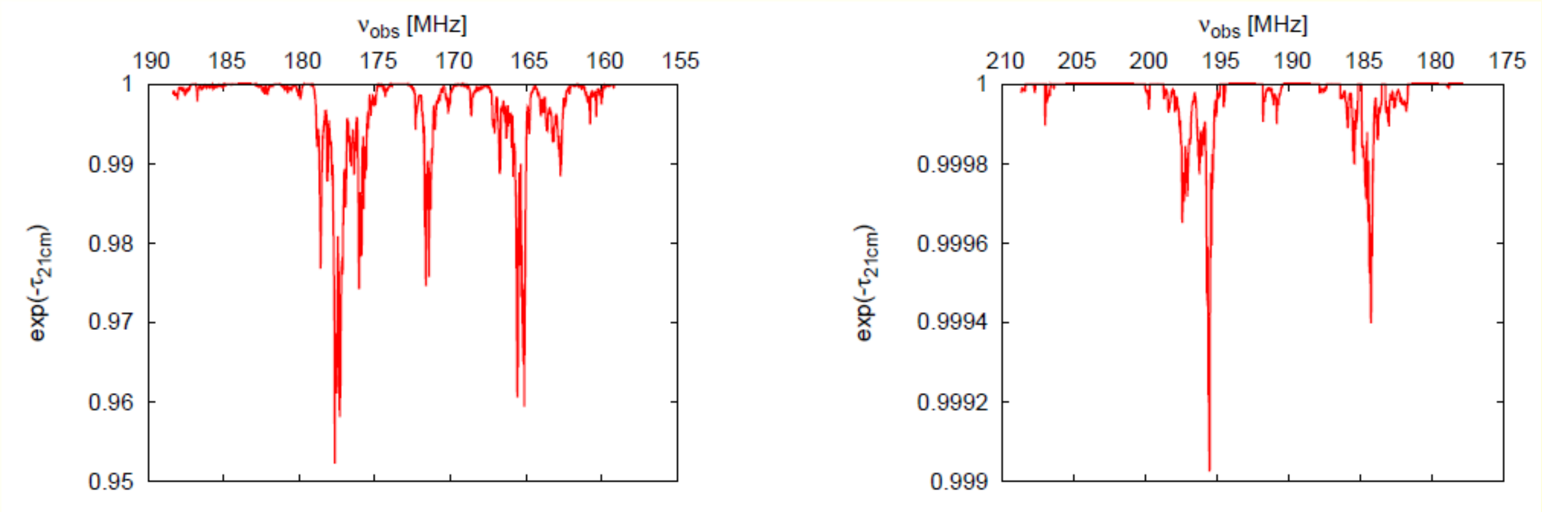
← L(UV)

Proximity effect of quasars



Powerful quasars ionize up to 80Mpc!
→ Allow escape of Lyα photons
Example of J0836+0054 at z = 5.802
3 LAE observed in the bubble, behind the QSO at 300-800kpc

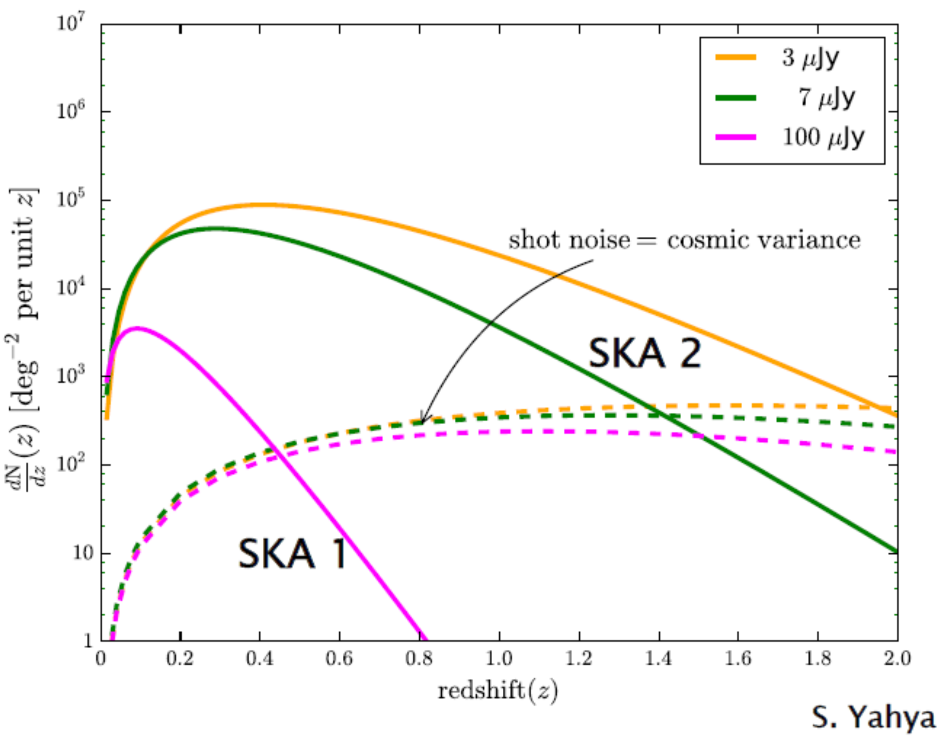
With SKA, detection of the 21cm-forest

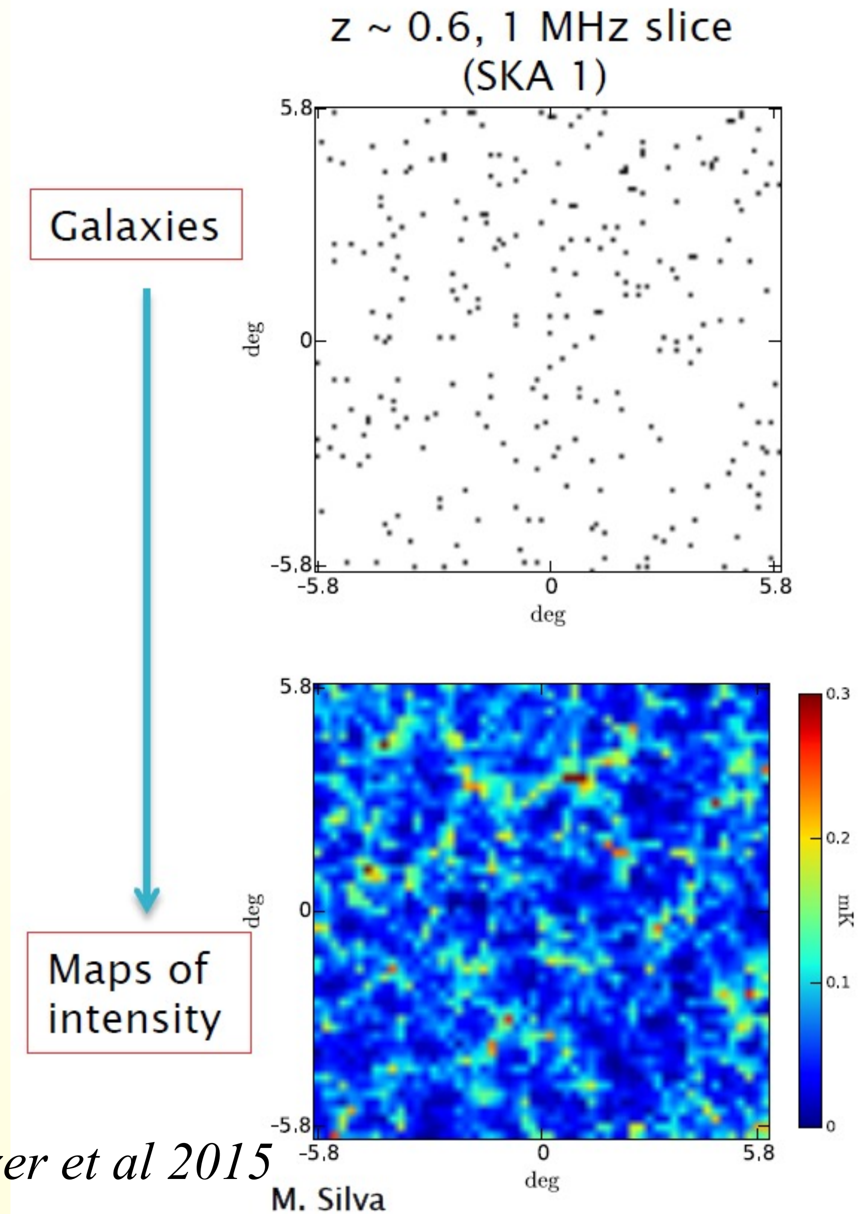


$<\tau_{21cm}>$ ~ 0.05 at z=7.9, and ~0.001 at z=7

Semelin et al 2015

HI intensity mapping



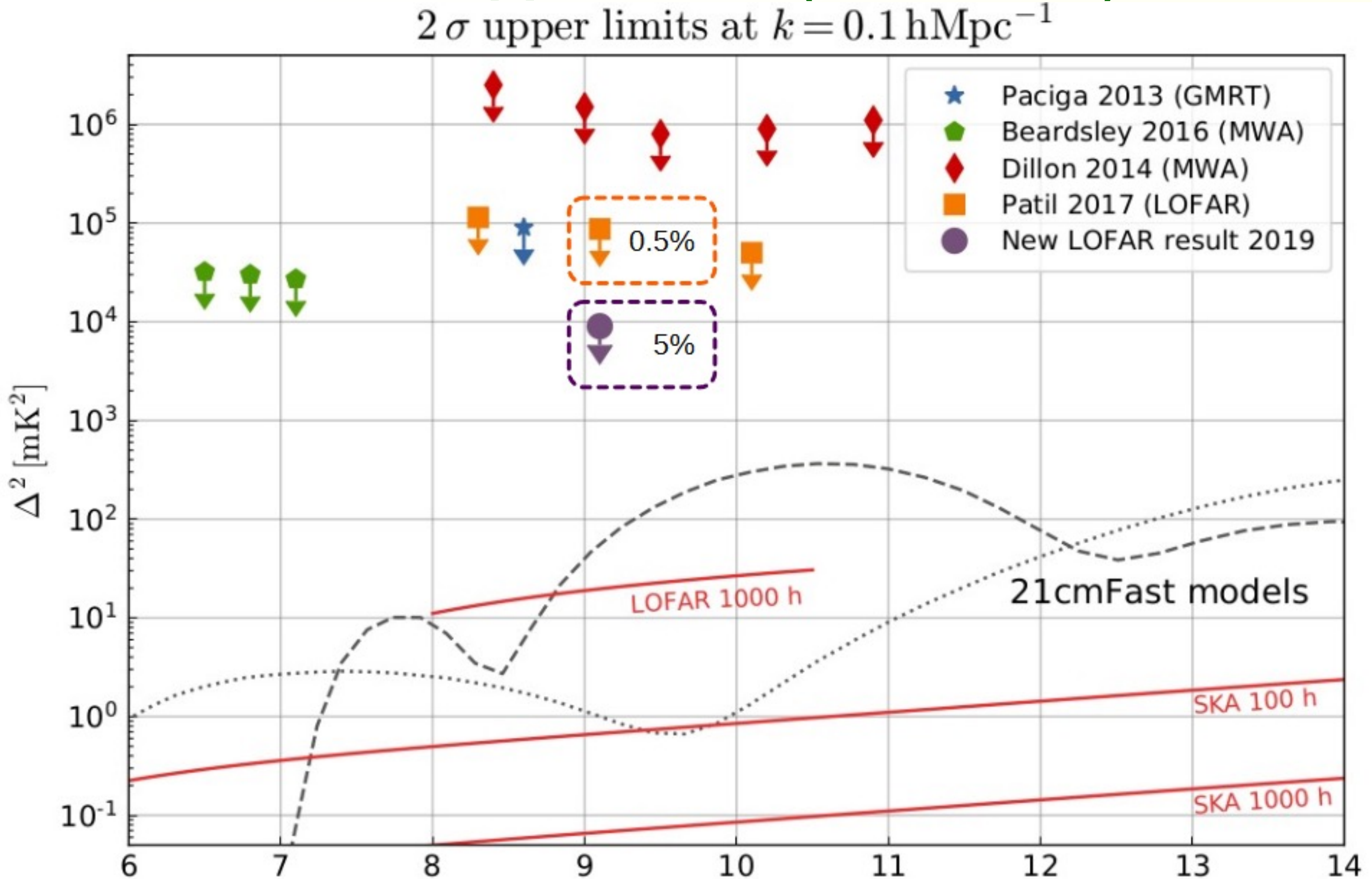


HI intensity mapping: main problem is the foreground, due to continuum

1000 x the expected signal

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

LOFAR upper limits (5% of data)



140h calibrated

Mertens et al. 2020

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

Norris et al 2015

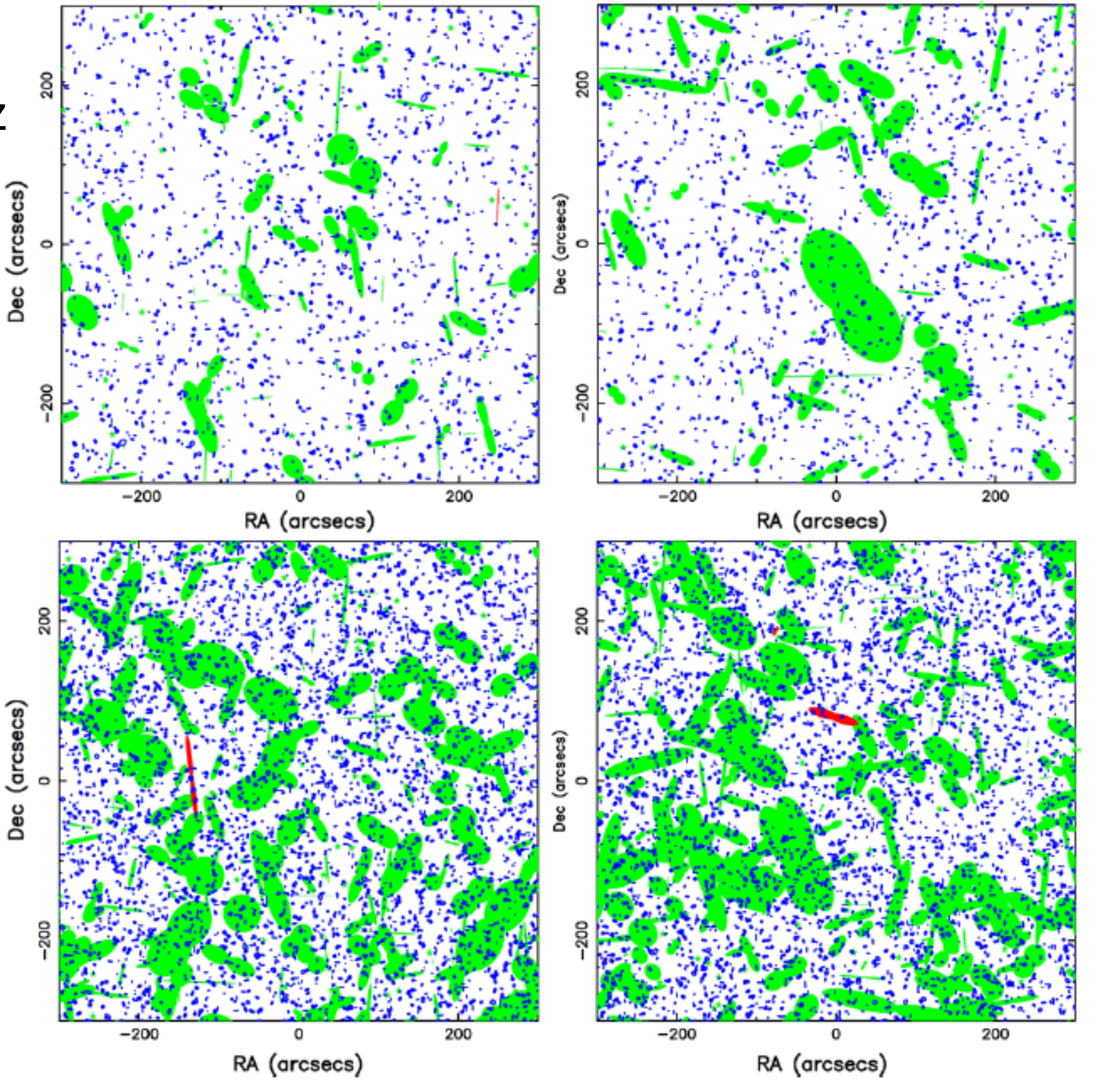
Deep radio sky
10' size, @ 1.4GHz

1mJy top
100nJy bottom
Left and Right
Cosmic variance

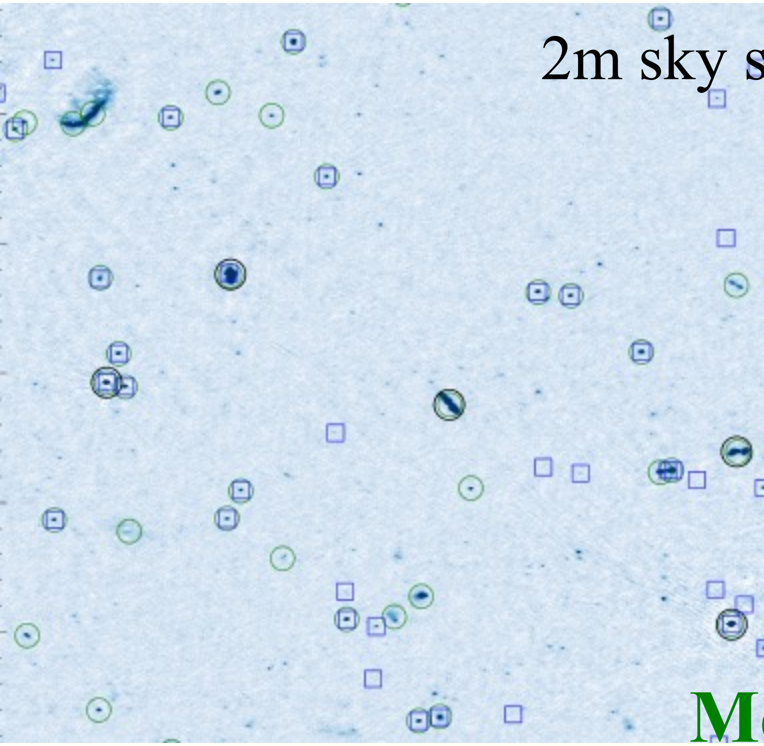
FRI: green, double
FRII: red, double

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

Jackson 2004

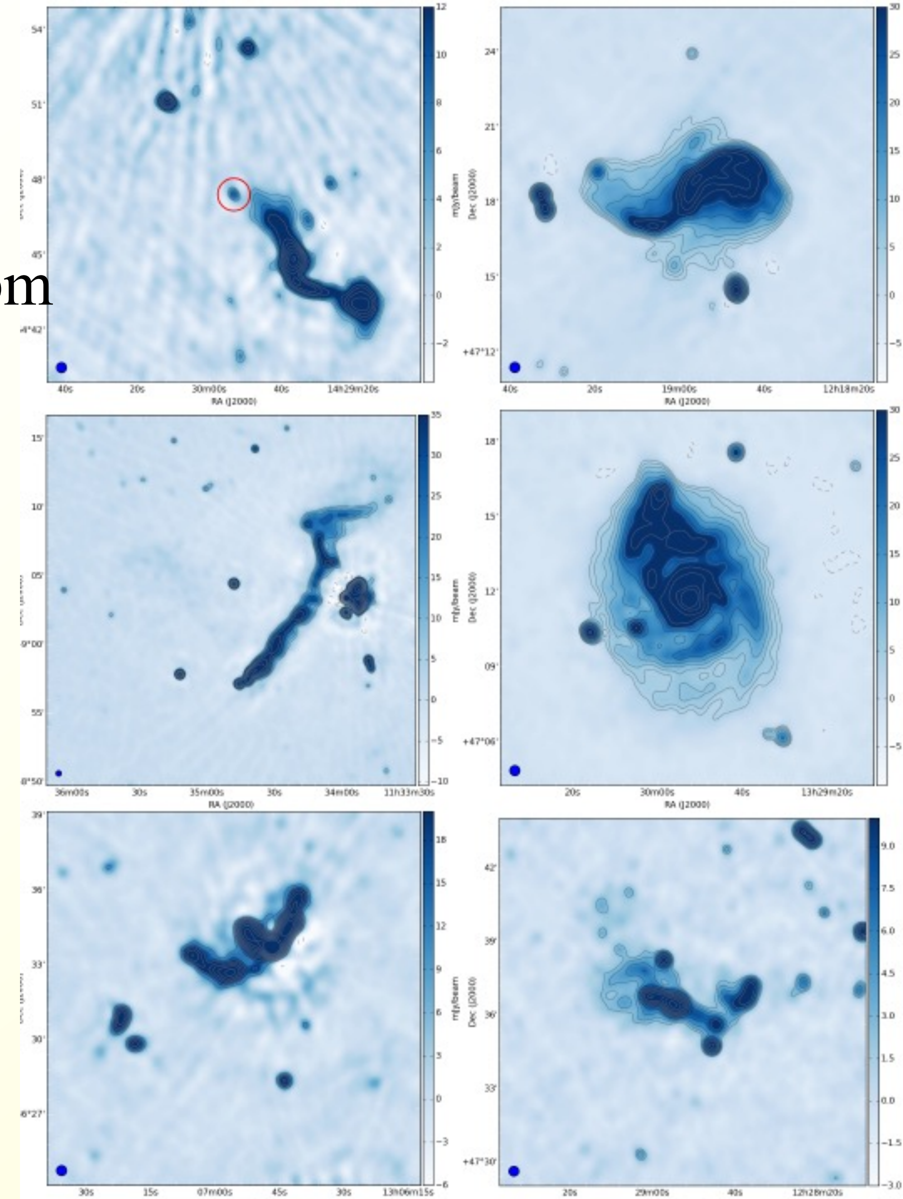


LOFAR LOTSS

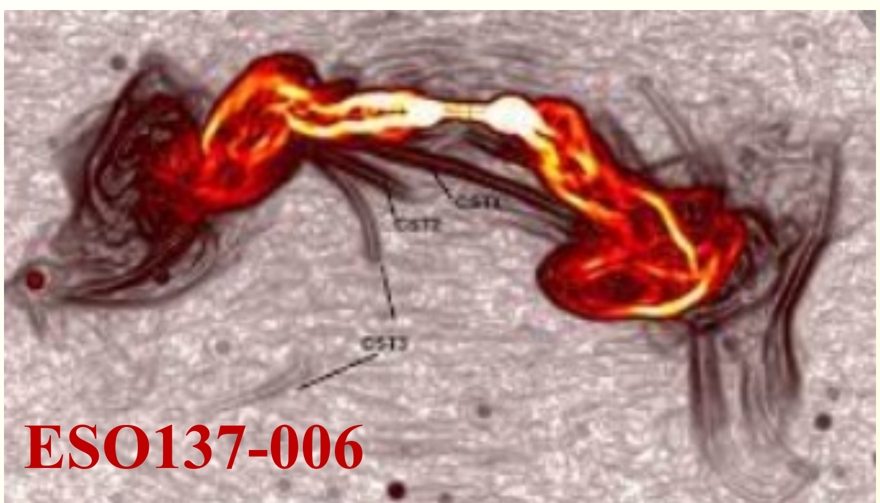


2m sky survey

100μJy/bm

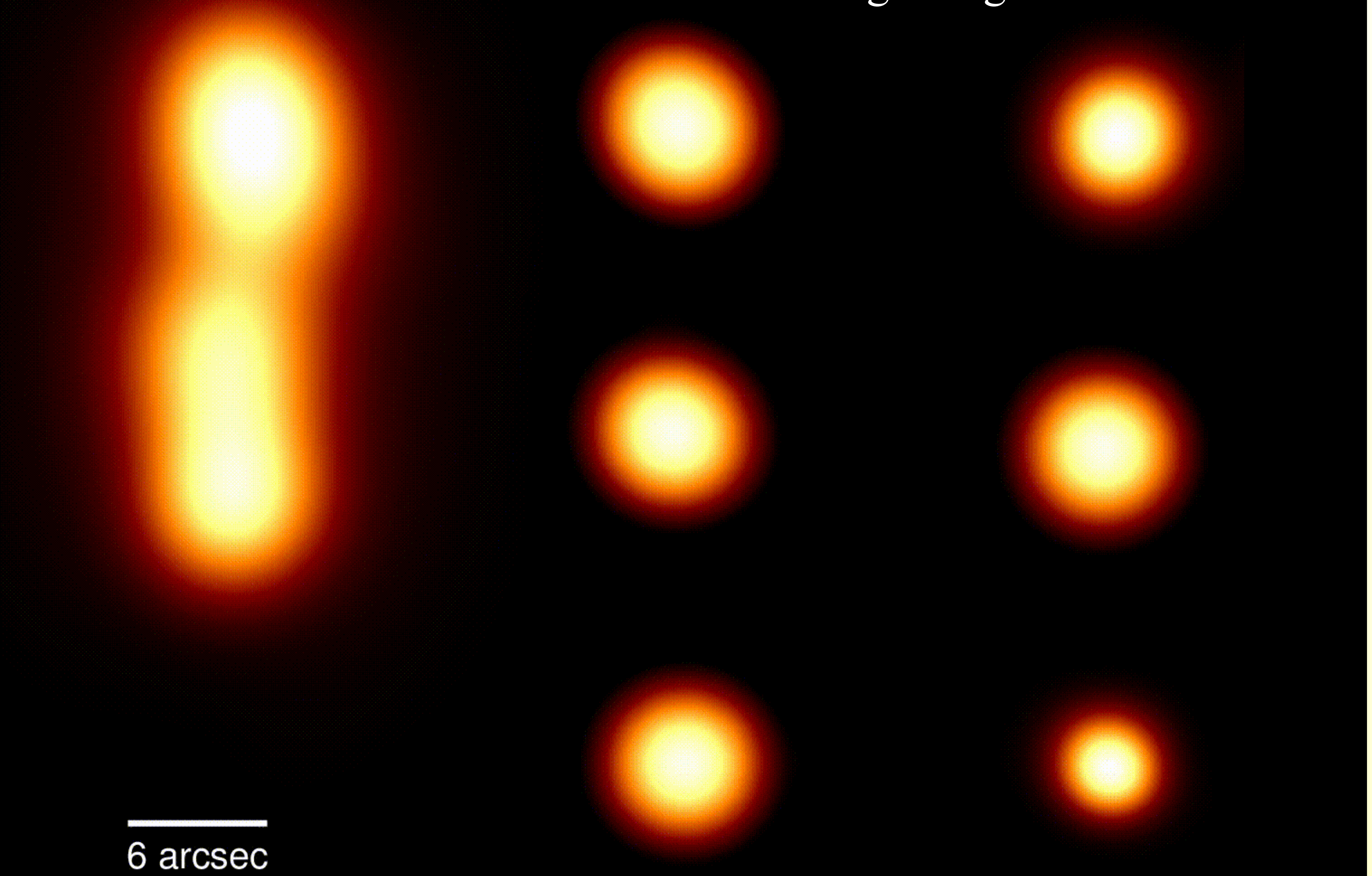


MeerKAT

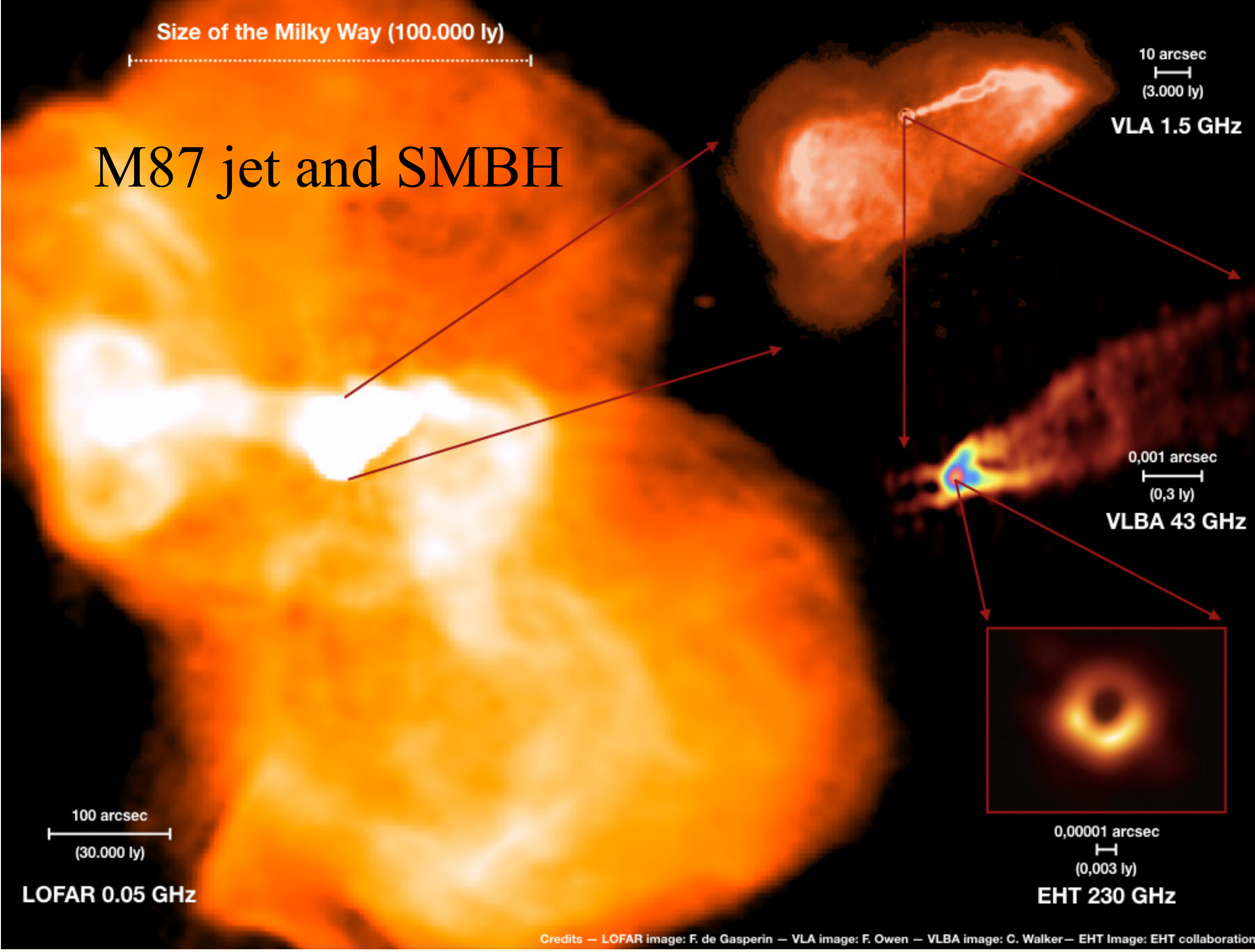


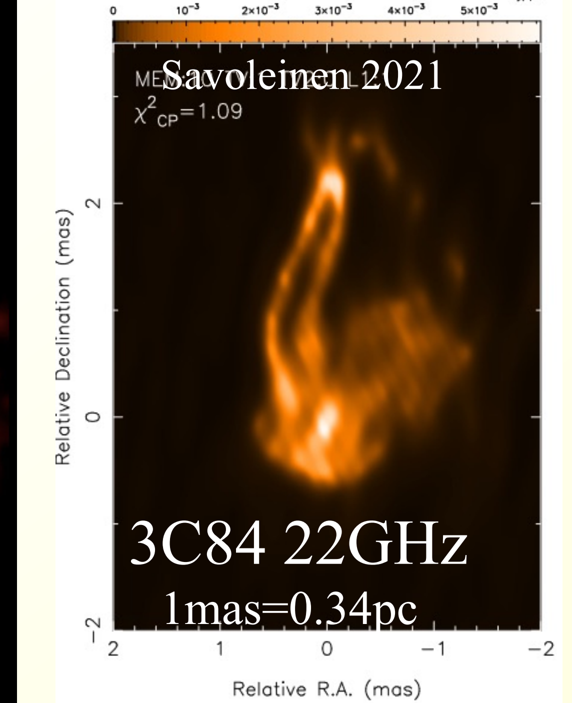
New synchrotron features in between radio lobes

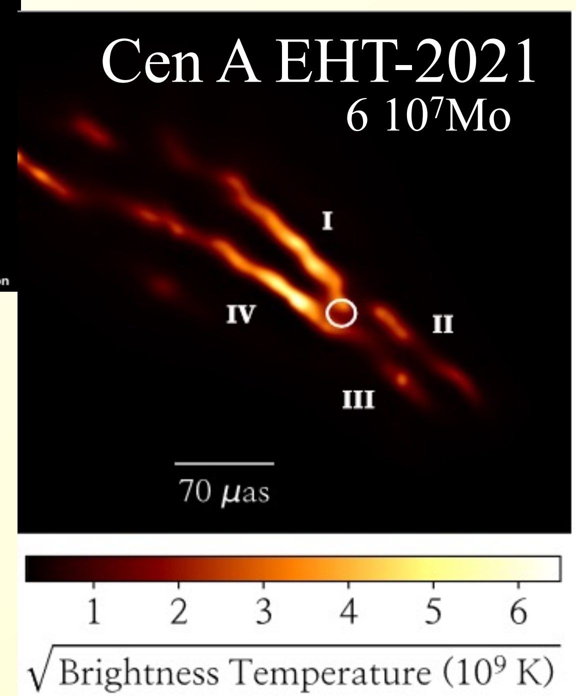
Going to high resolution



From Leah Morabito, KSP LOFAR

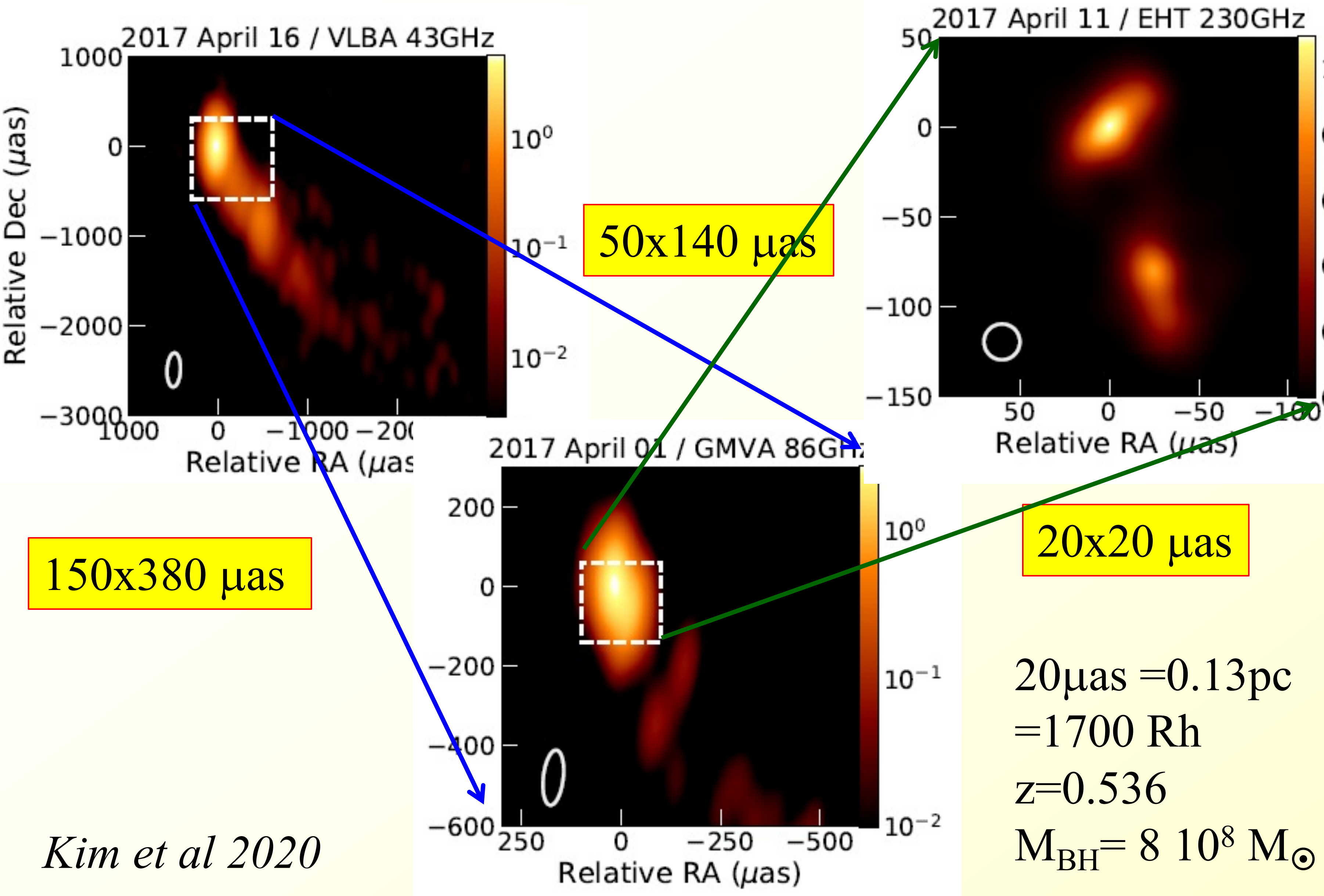






Huge progress in spatial resolution
High dynamical range
EHT Event Horizon Telescope

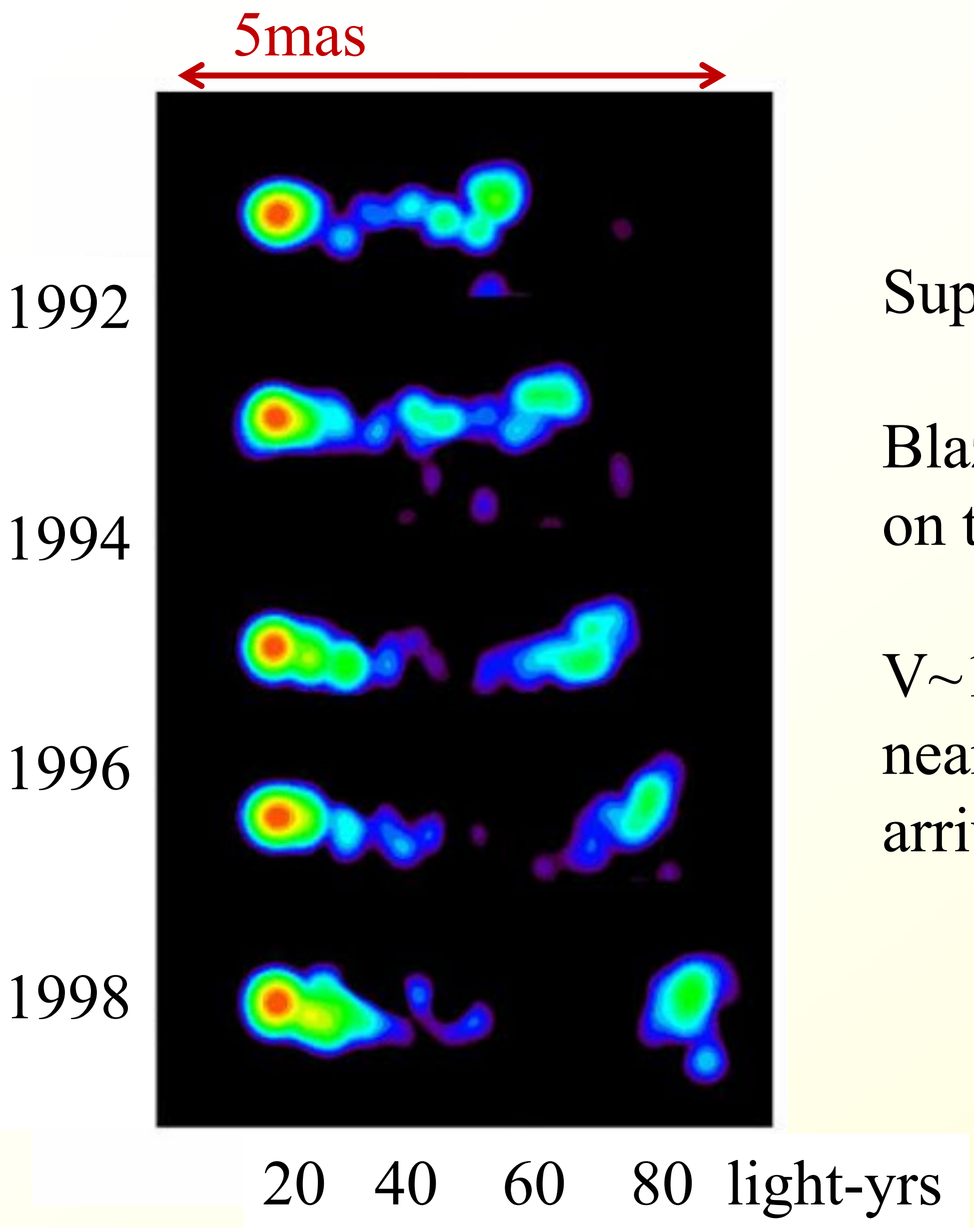
VLBA, GMVA, EHT: 3C279 blazar



20μas =0.13pc
=1700 Rh
z=0.536
M_{BH}= 8 10^8 $M_\odot$

Kim et al 2020

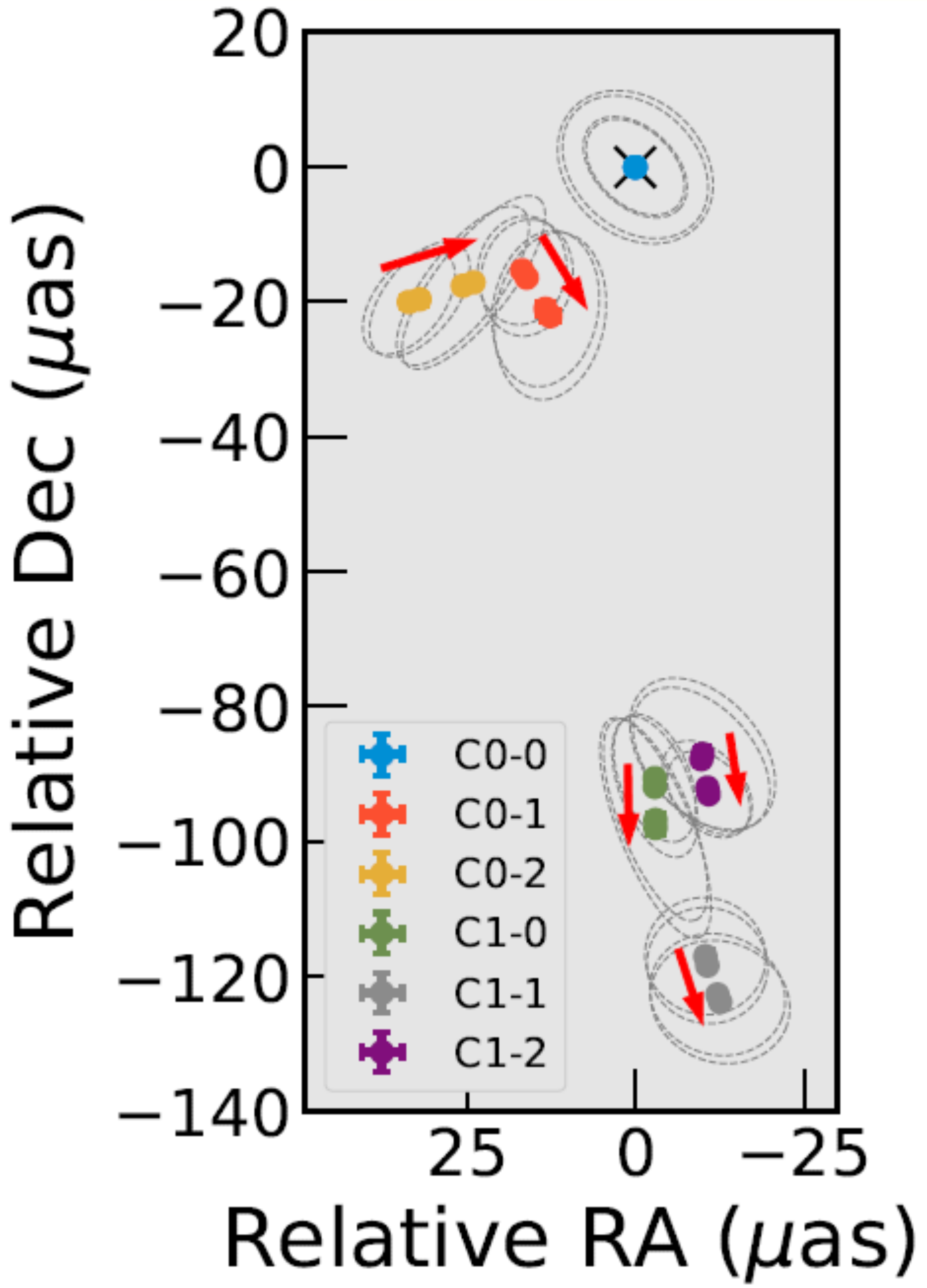
3C279 jet at larger scale



Super-luminal apparent V

Blazar: the jet is almost aligned on the los

V~10c, since the signal emitted nearest to the observer arrives earlier



Proper motions April 5-11 2017 (EHT week)

Velocities of 15c & 20c non radial
Rotation? Shocks?

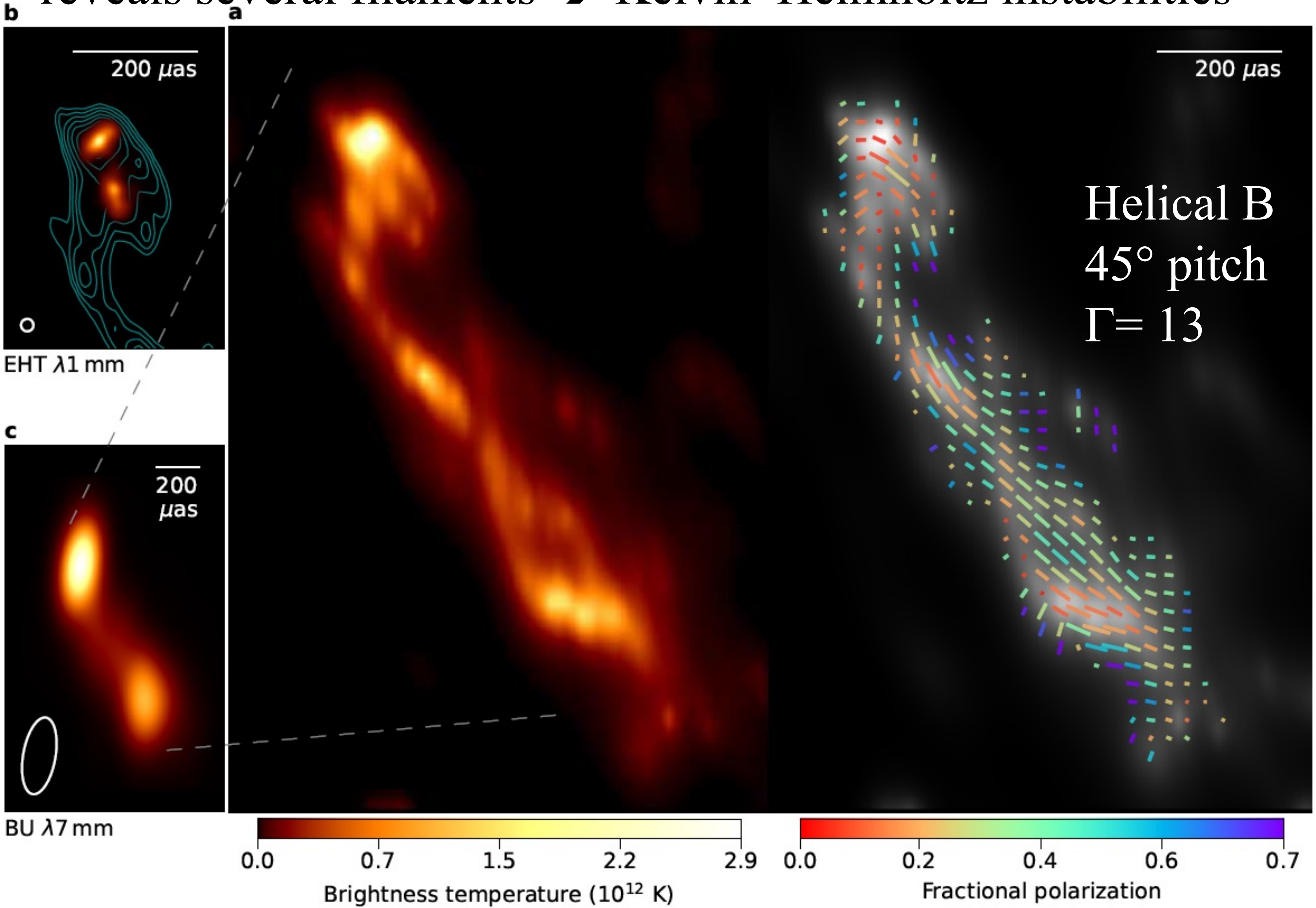
Resolution 20μas
=0.13pc
=1700 R_h

M=8 $10^8 M_\odot$

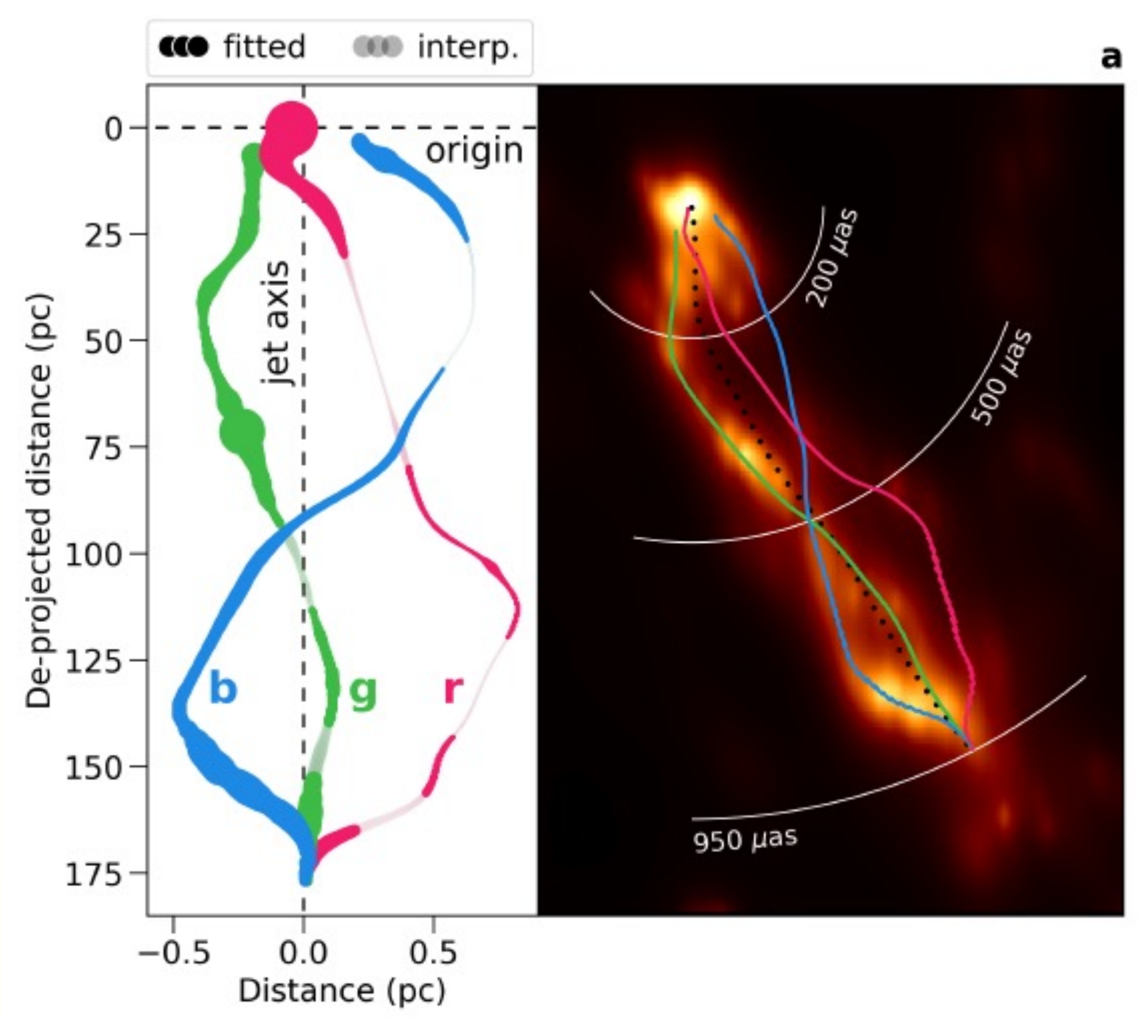
z=0.536
C0 is the nucleus

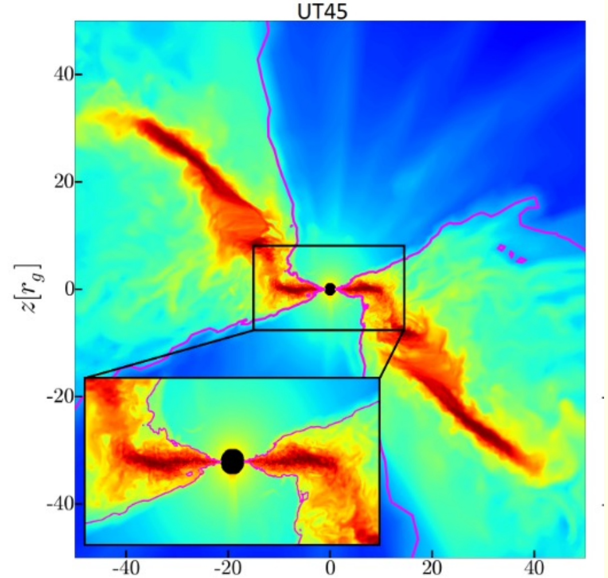
RadioAstron, Space VLBI (300 000km: 22GHz ou 1.3cm)

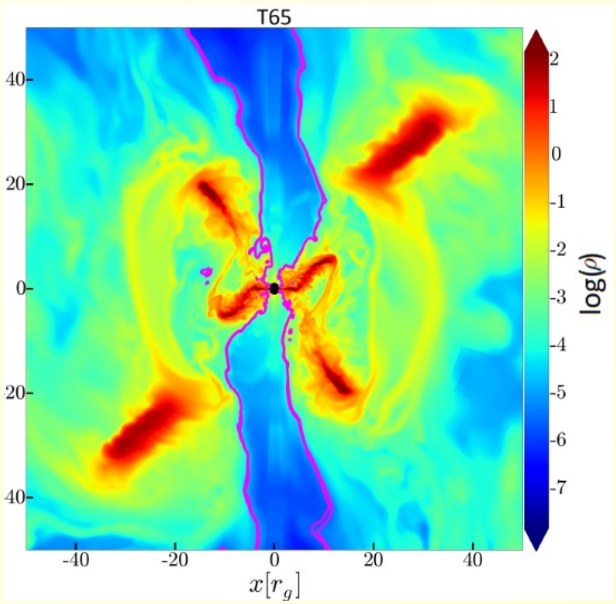
Jet resolved transversely: *Fuentes et al 2022*
reveals several filaments ➔ Kelvin–Helmholtz instabilities



Fuentes et al 2022







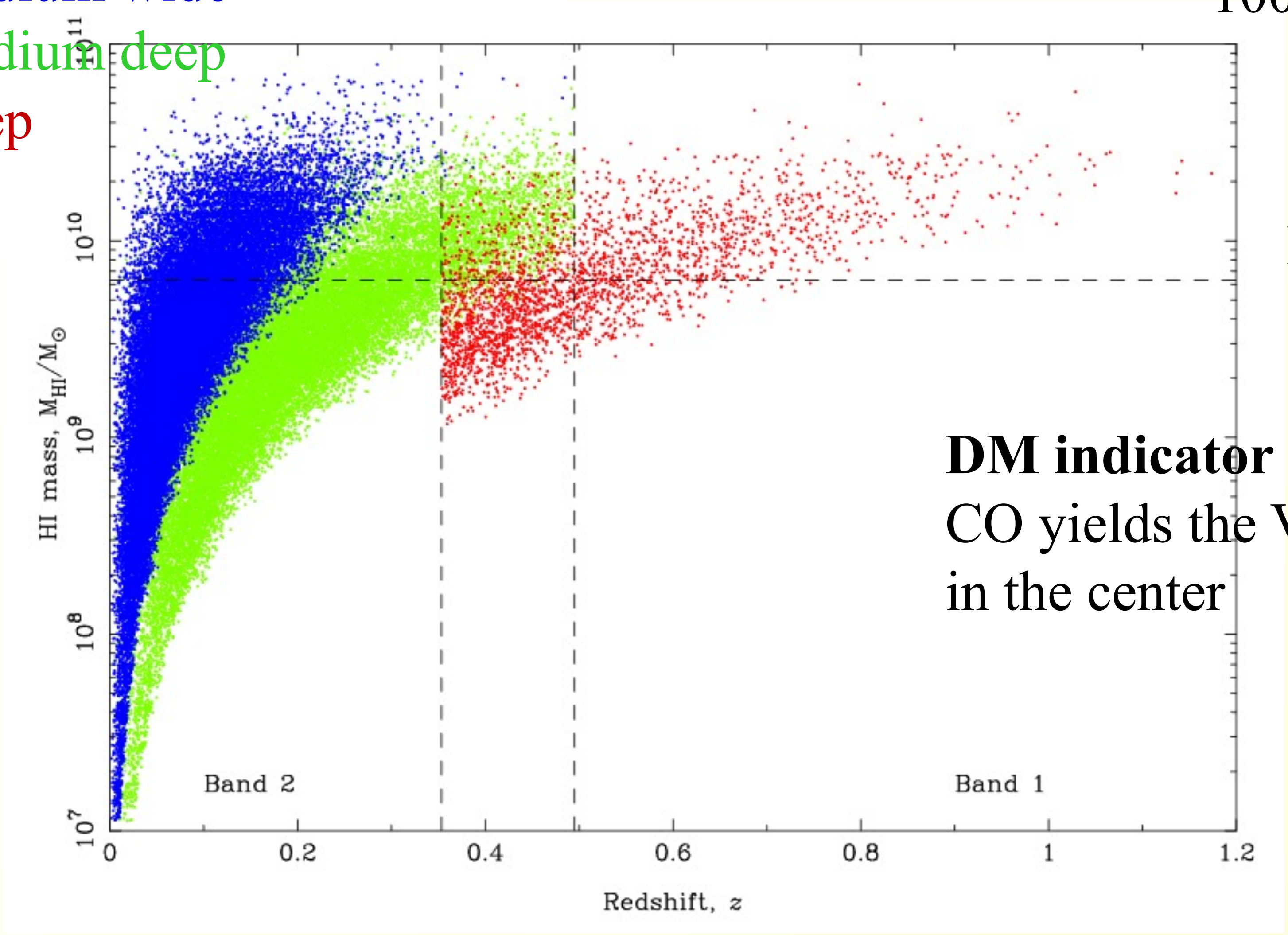
BH spin not aligned with accretion
disk material➔ torques and precession

Liska et al 2021

HI gas & dark matter in Galaxies

Medium wide
Medium deep
Deep

1000h survey



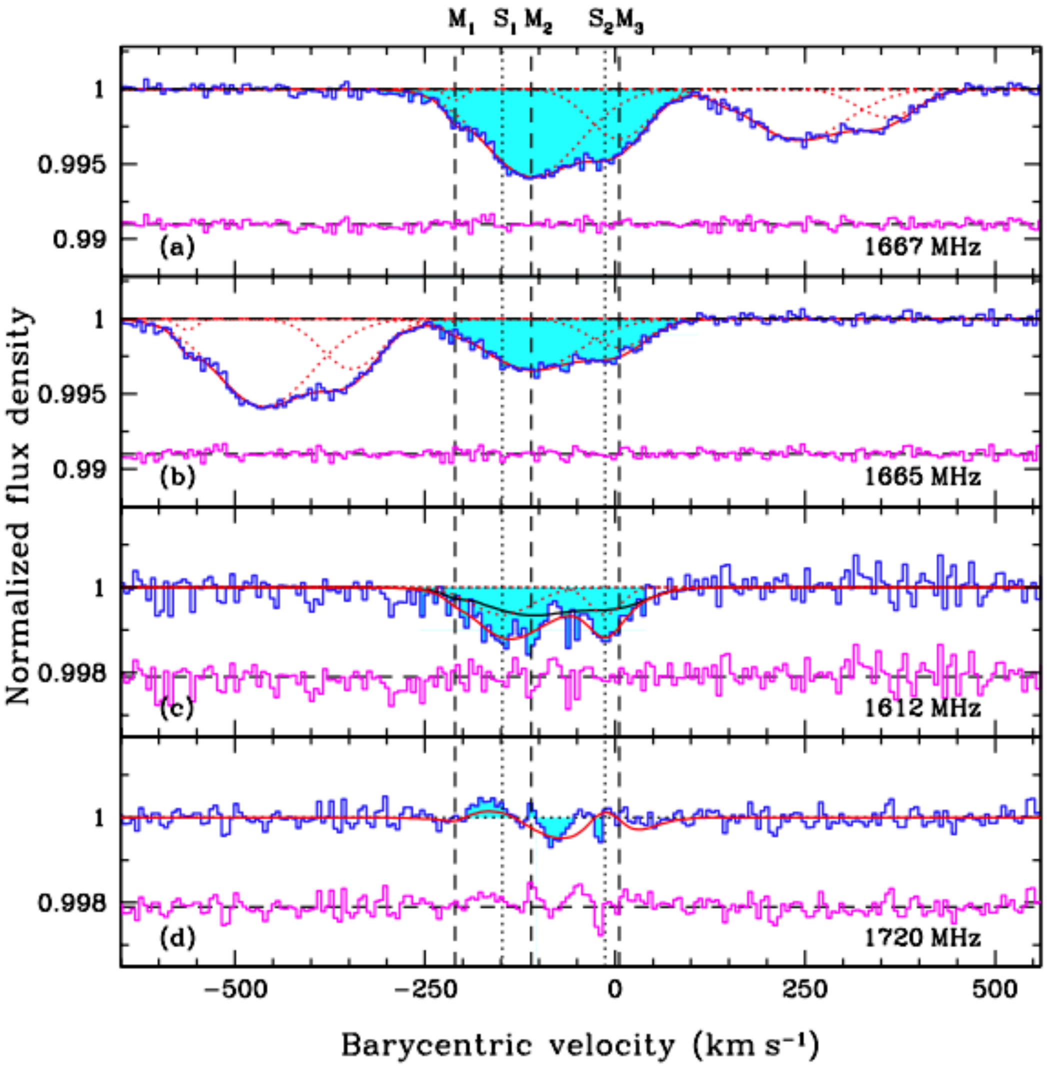
MHI* z=0

DM indicator
CO yields the V-gradient in the center

Study of HI rotation curves up to z~1 with SKA1
Up to z~2 with SKA2

Staveley-Smith & Oosterloo 2015

PKS1830 OH absorption



1612 and 1720MHz are conjugate lines

When 1612 in emission → 1720 in absorption, and the reverse

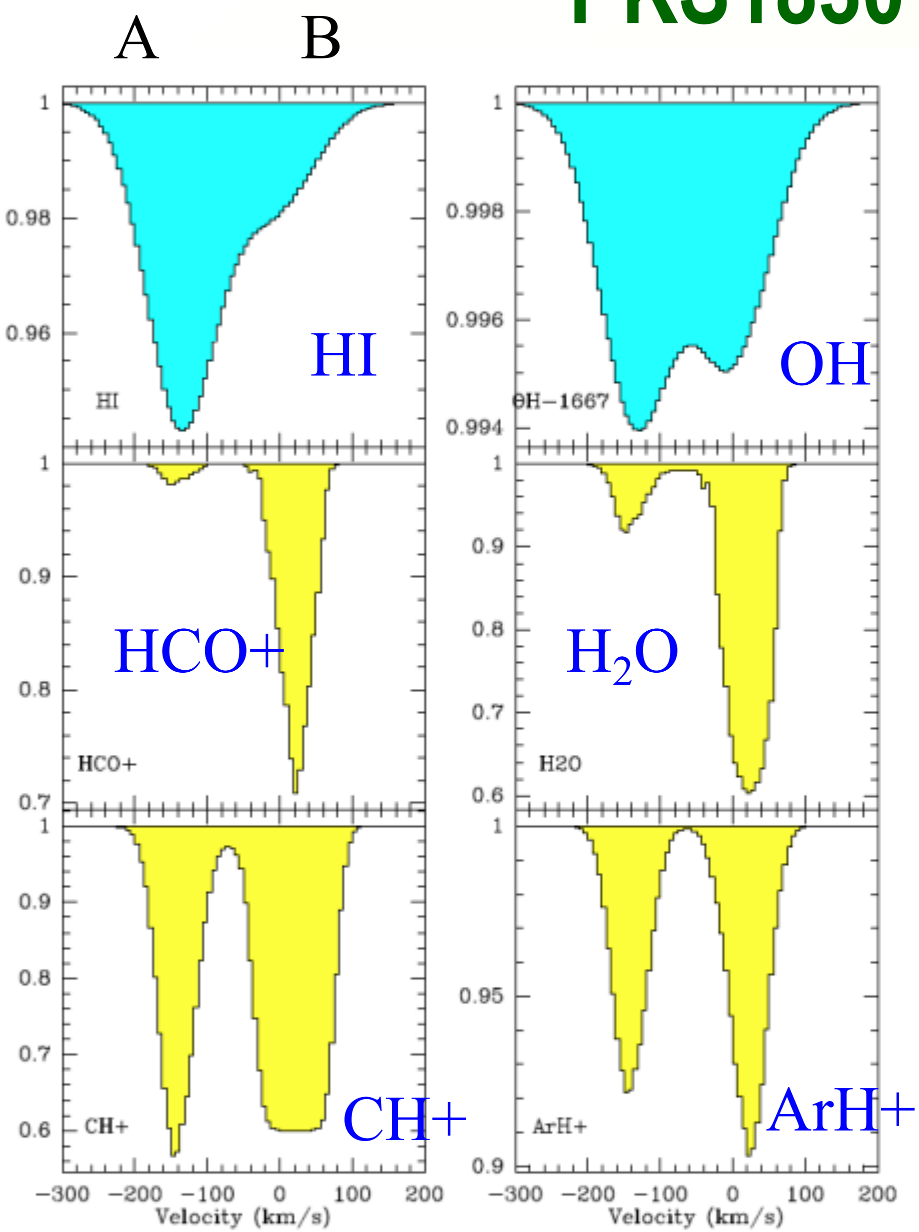
Black line; LTE expectation from M1, M2, M3

Difference black-red is the maser contribution due to pumping

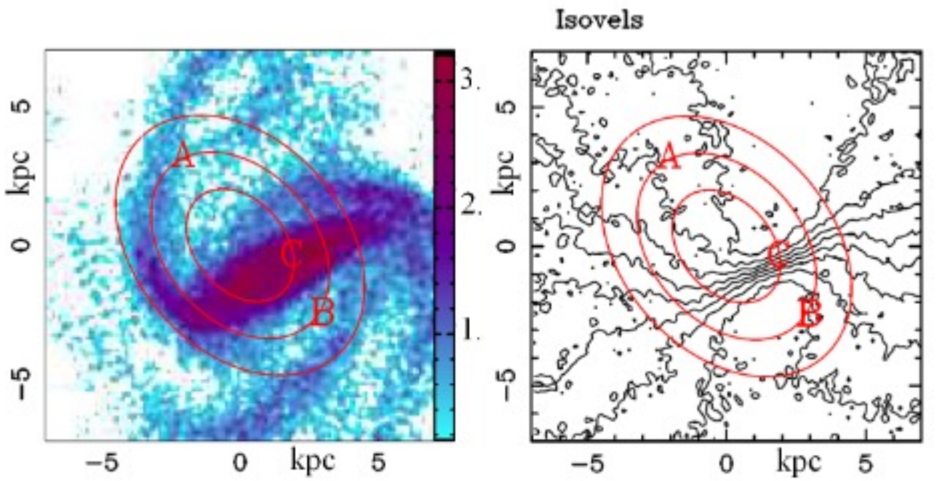
1720 emission L=6100 Lo

Most luminous known

PKS1830 absorption models



Model with a barred spiral disk
Off-centered with the continuum
Behind (lens center closed to C)

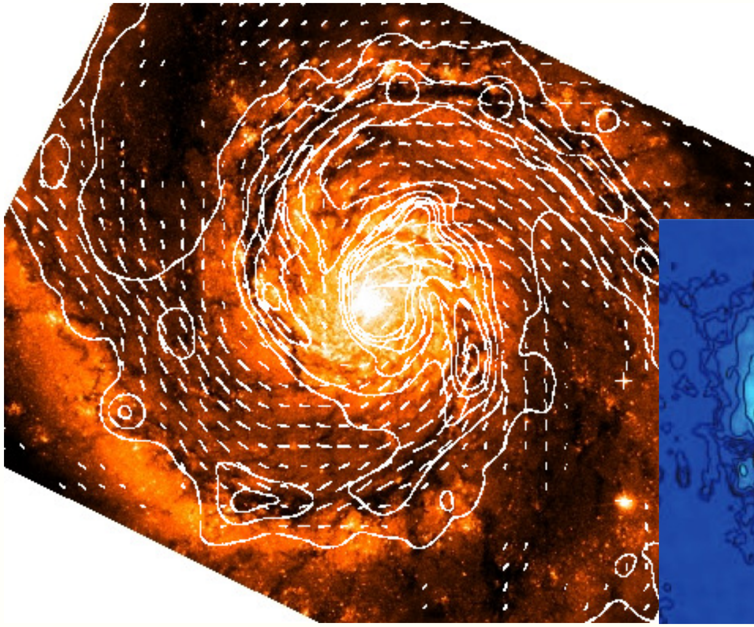


Isovels from -110 to 110km/s
A(NE) B(SW) and C images
i=20-30°, PA=12° ΔV=150km/s

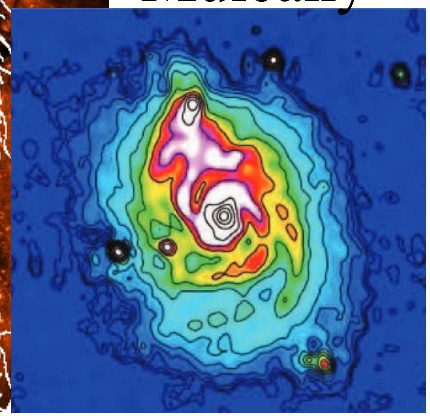
Combes et al 2021

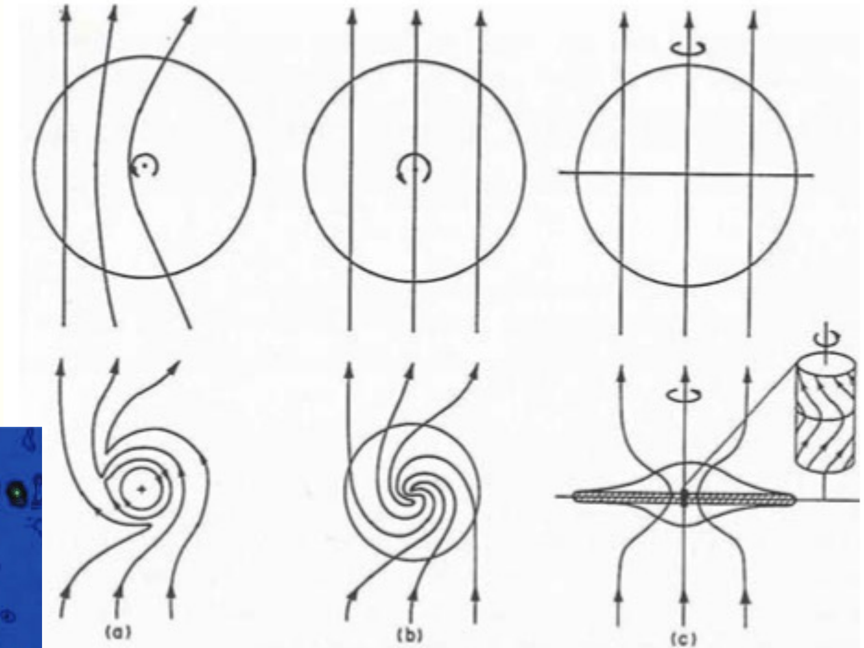
Magnetic fields

M51, Beck



LOFAR
Mulcahy





Sofue 1990

All sky survey of Faraday rotation (n_e, B): to measure inter-galactic B together with B inside galaxies

Magneto-genesis: Inflation, phase transitions in the early Universe

Then **batteries** to amplify B. Normally B frozen into matter, should dilute away in the expansion. When structures collapse, B is amplified

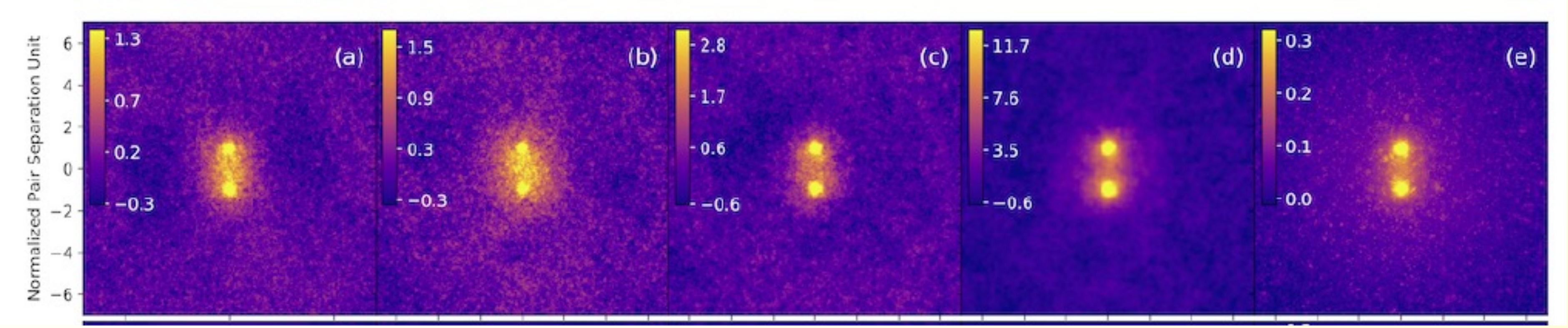
Detection of inter-galactic B is s strong goal (e.g. cool core clusters)

Discovery of cosmic B through stacking

Diffuse filaments connecting clusters ➔ the cosmic web (15Mpc scale)
X-ray hot has, eRosita (Reiprich et al 2020), $T=10^5$-10^7 K, ρ10-100 <ρ>

LOFAR direct synchrotron, in filaments (Govoni et al 2019, Botteon et al 2020)
But short scales. Now with GLEAM (MWA survey)

GLEAM 154 MHz, 118 MHz, 88 MHz, OVRO-LWA 73 MHz, ROSAT 0.1 -2.4 keV

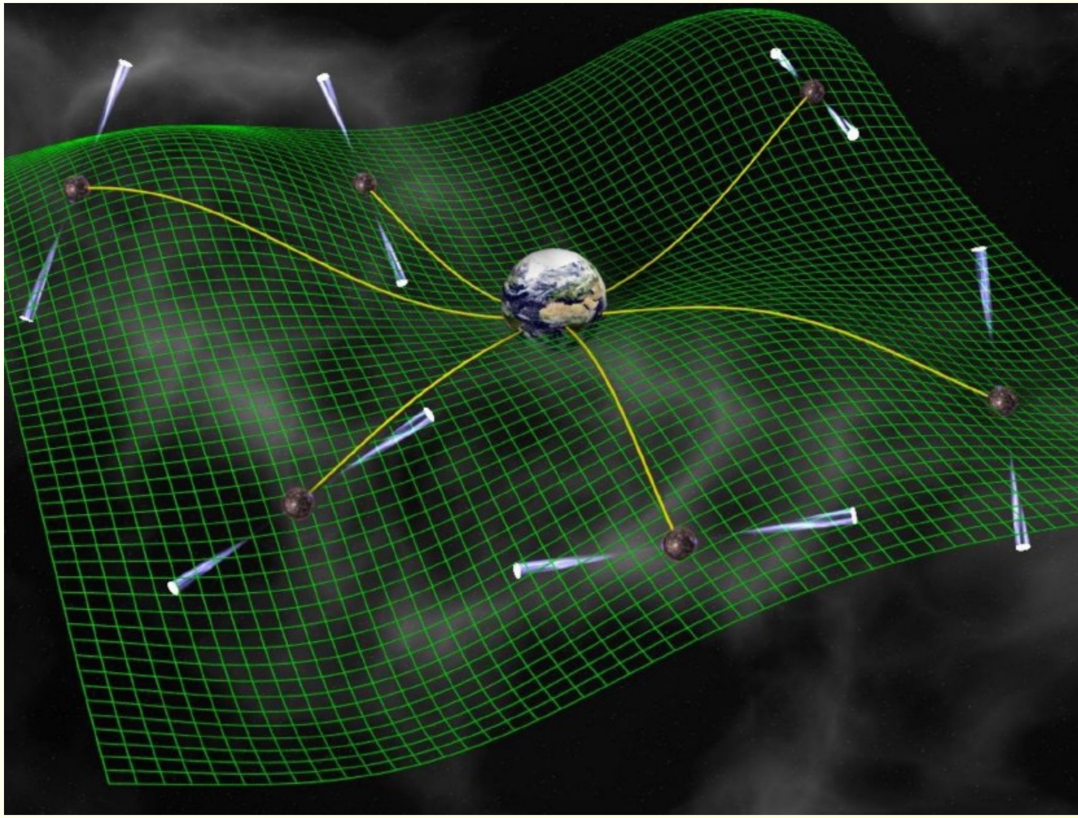


First large-scale filament detection, **B=30-60 nG** ➔more highly magnetised than previously believed, subject to more efficient shock acceleration

Vernstrom, Heakd et al 2021

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



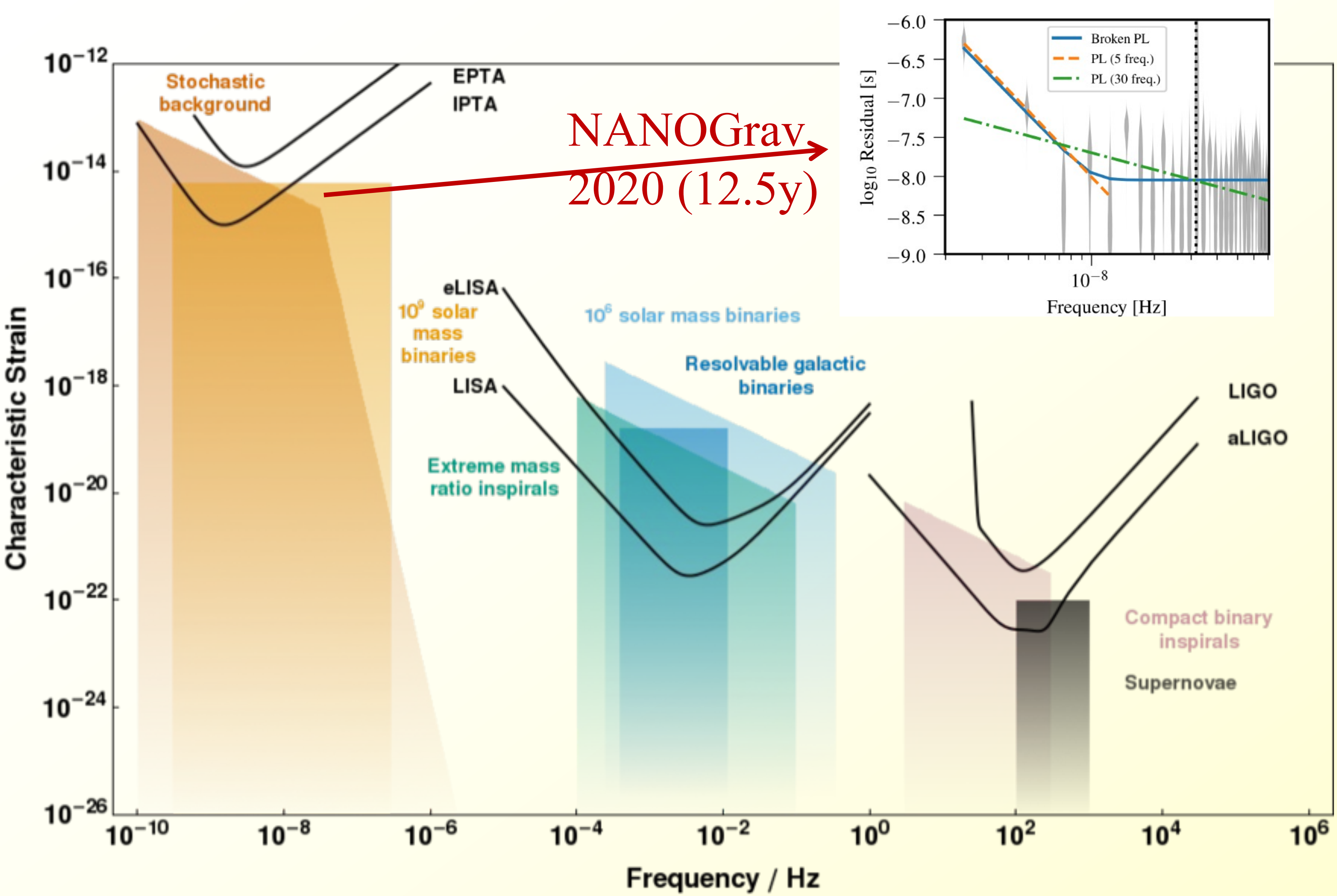
➔GW $\lambda \gg \lambda$ (LIGO-Virgo)

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)

GW with Pulsars

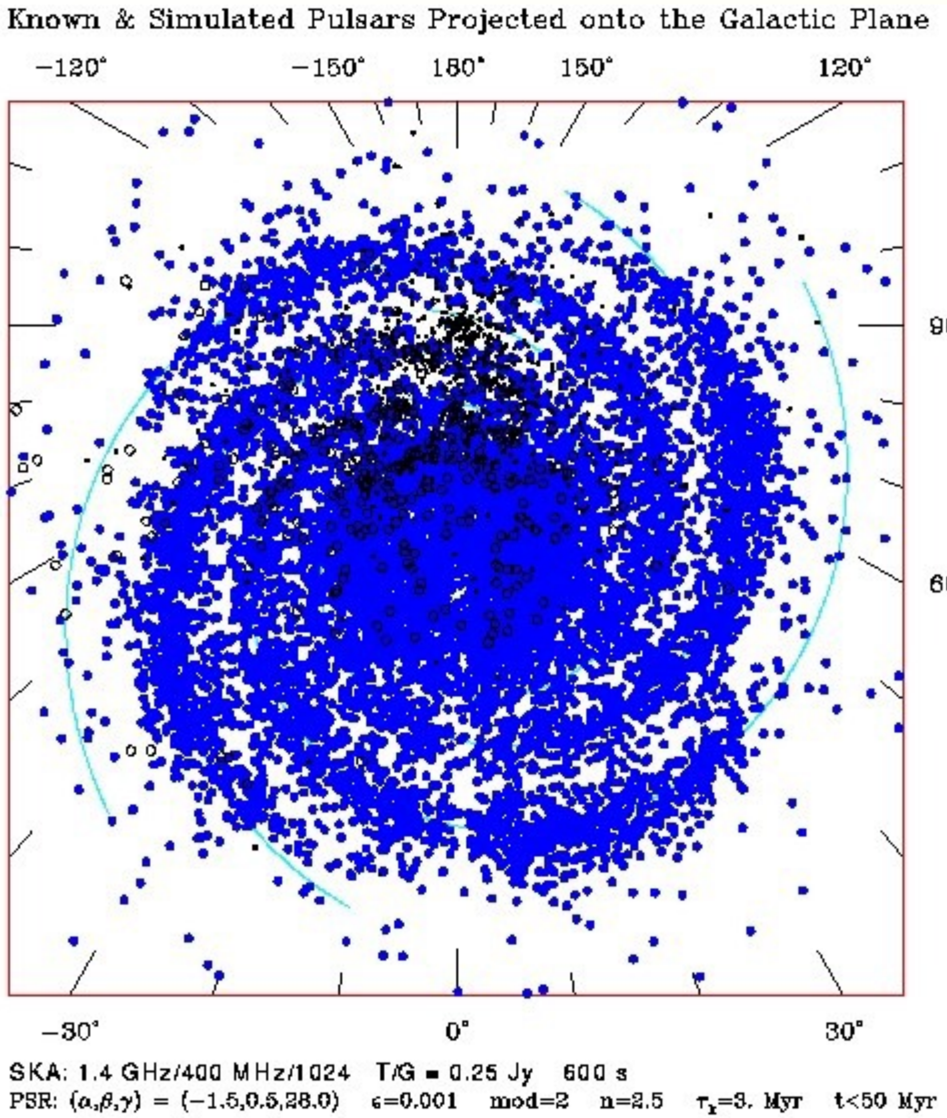
EPTA: European Pulsar Timing Array - IPTA International



Nano-frequency λ~ 10ly

Pulsars with SKA

J Cordes, 2004



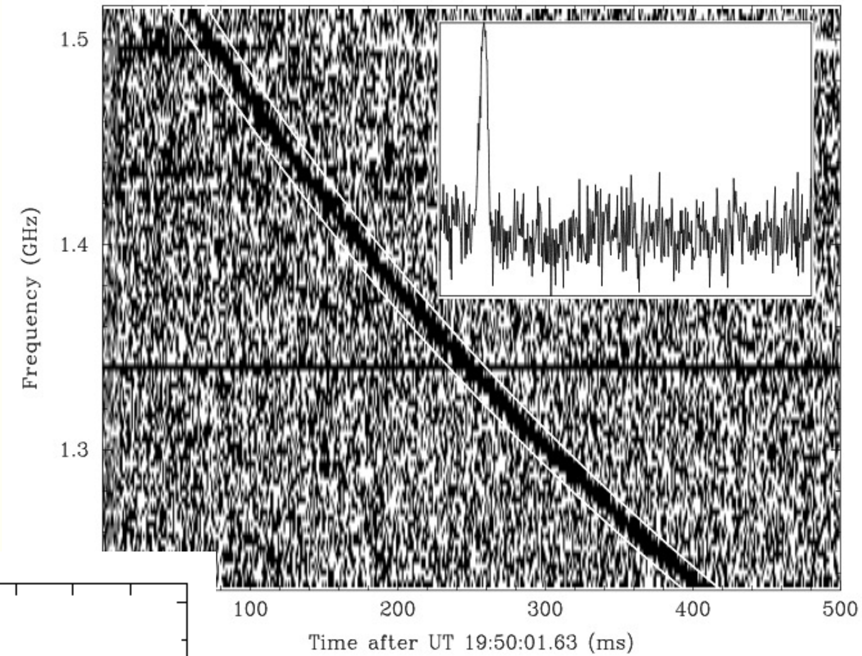
MW: 30 000 PSR, 10^4 MSP
~20,000 potentially visible normal pulsars, MSPs and RRATs = **Rotating Radio Transients** *(irregular, nulling, might be more abundant?)*

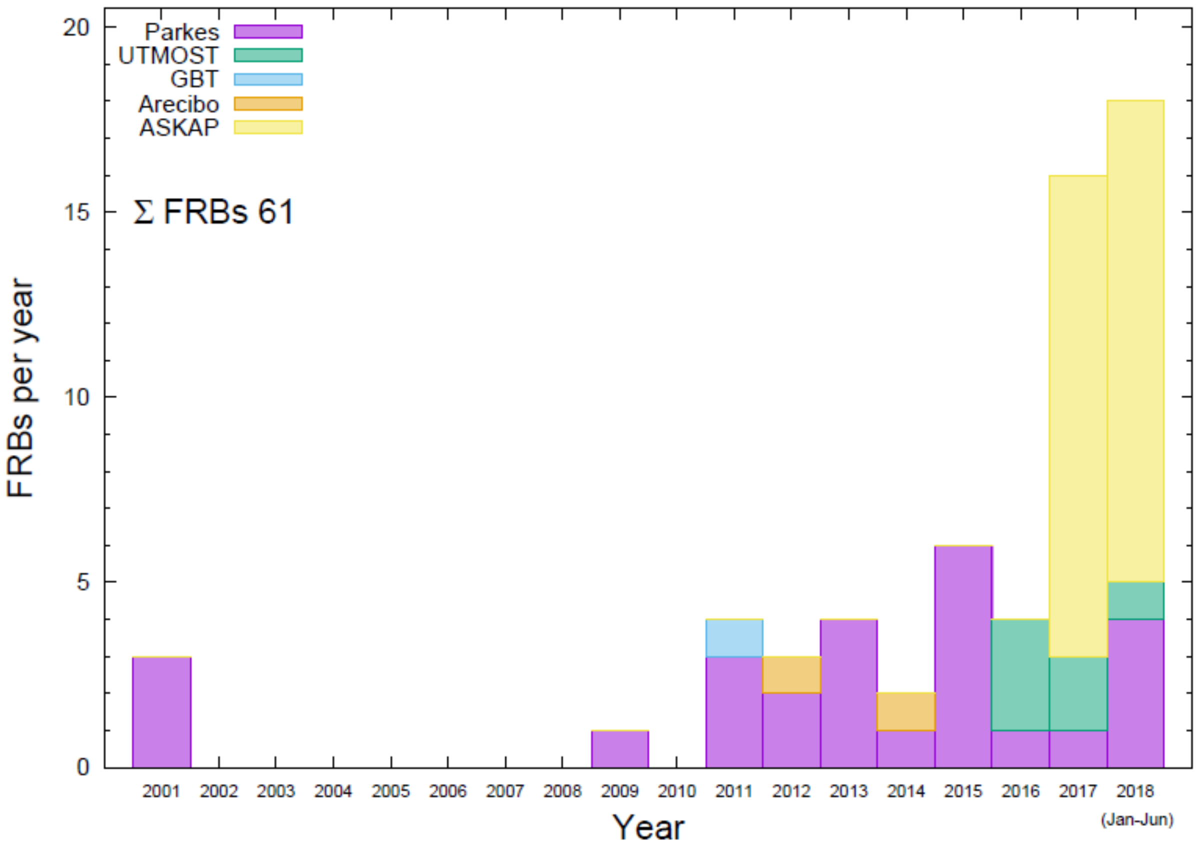
- SKA1 has the potential to find a large fraction (~50%?) of these pulsars

+ 7000 FRB/day in all sky

FRB: Fast Radio Bursts

With SKA-MID, 100 FRB/yr
with precise localisation
Detections by ASKAP, CHIME
➔540 detected (~800/day/sky)

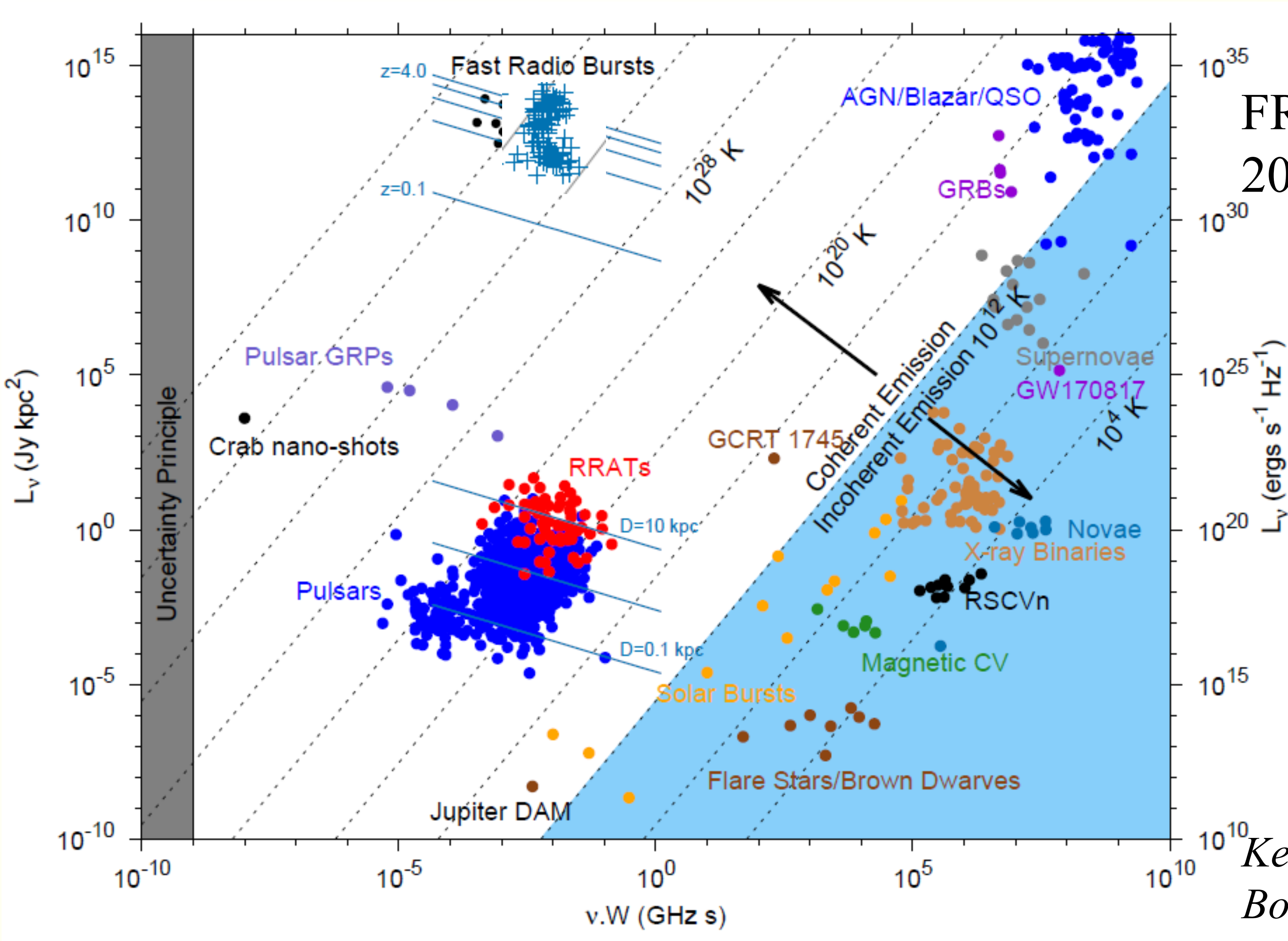




Lorimer et al 2007
Large DM==> far away
Powerful objects
In external galaxies
10μs variability
➔Compact objects
Strong B
➔ magnetars
Keane 2018

FRB in the transient diagram, L-νΔt

Could be use to trace the nature of Universe ➔ tomography

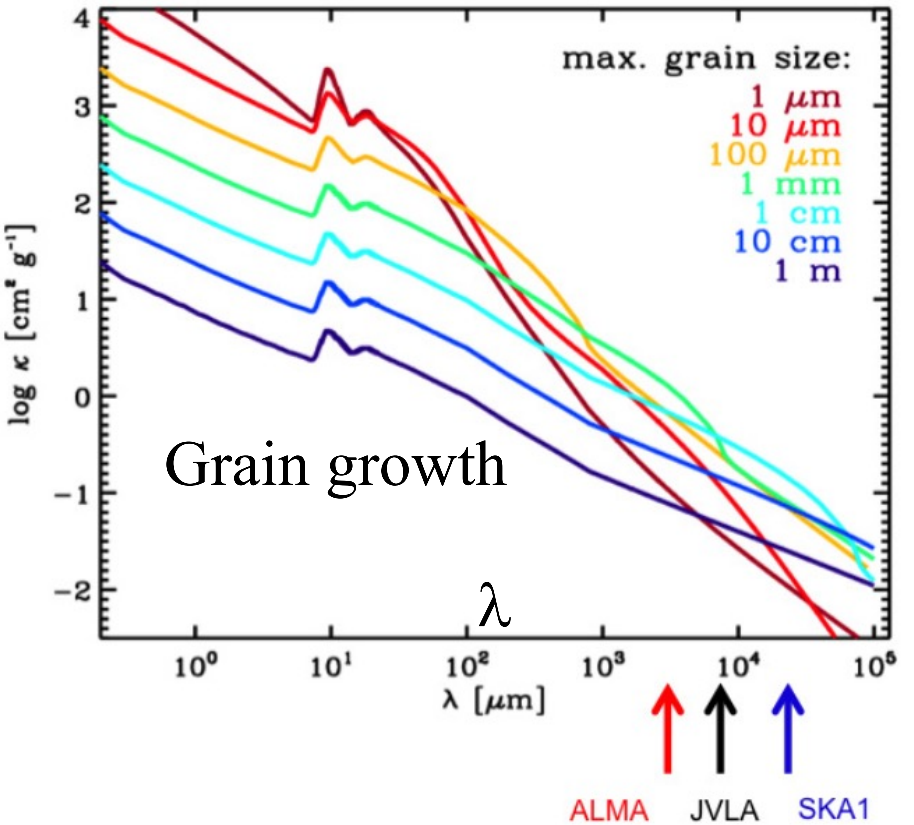


FRB121102+
20 repeaters

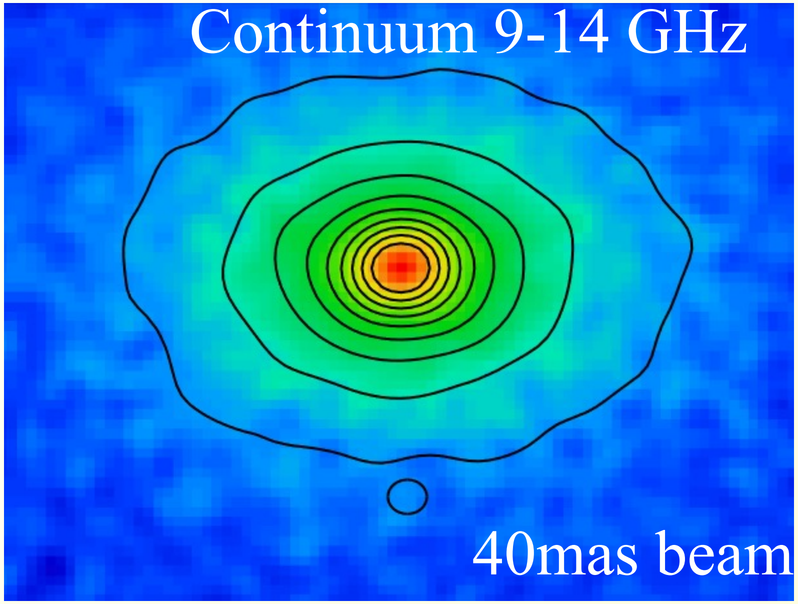
Keane 2018
Bochenek 2020

Cradle for Life with SKA

κ opacity

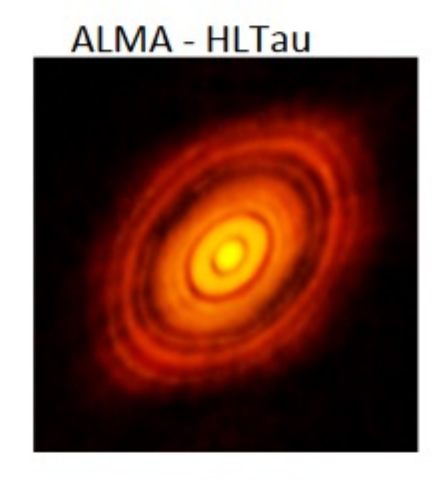


simulation



40mas beam ~4 AU
for the snow line in
the nearest systems

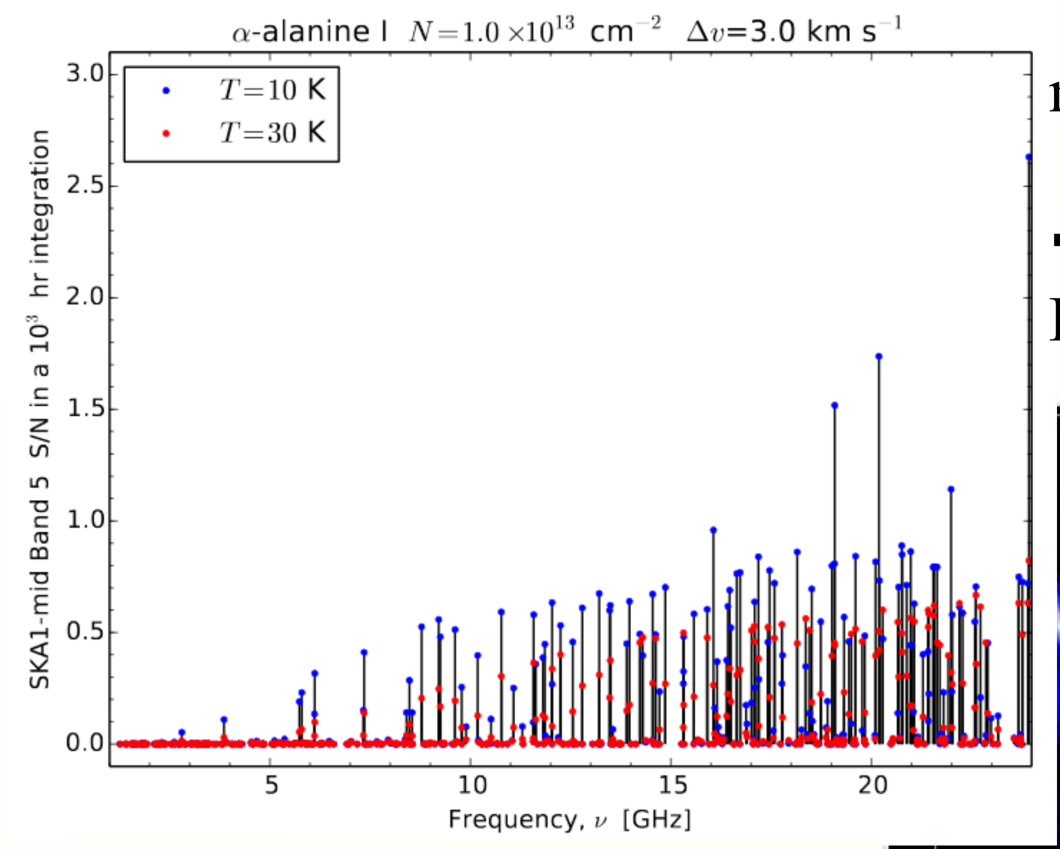
Hoare et al 2015



+ magnetic fields like Jupiter

Pre-biotic molecules

1000h SKA1-mid, α-alanine



In Synergy with ALMA!

CH_3OH,methanol

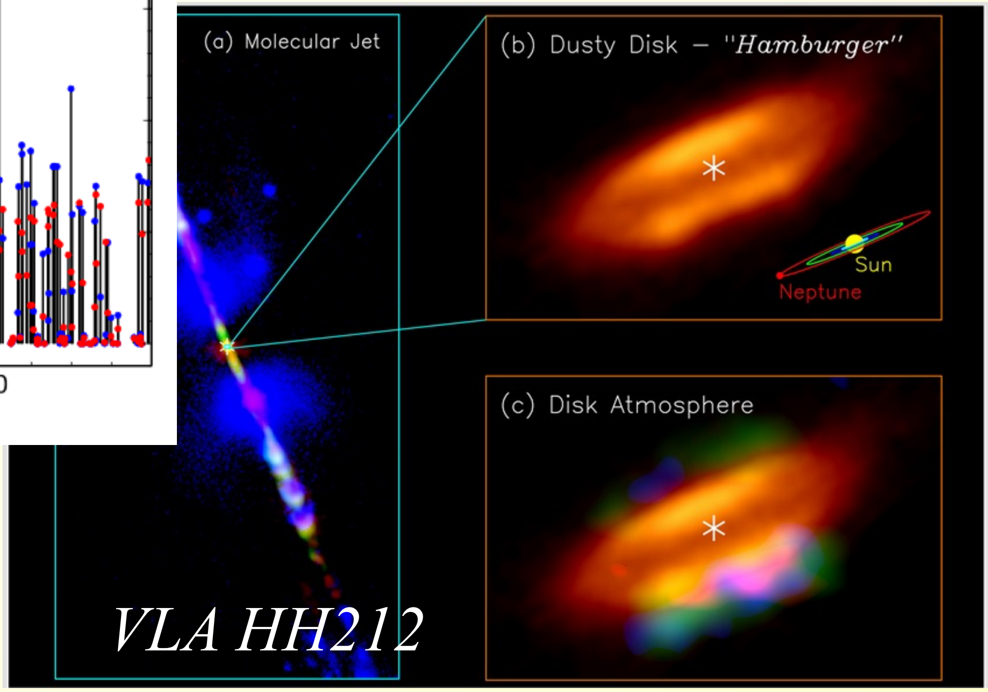
CH_2DOH, (deuterated)

methanethiol CH_3SH,

formamide NH_2CHO

➔ Amino acids, sugars

Heavy molecules, Band 5

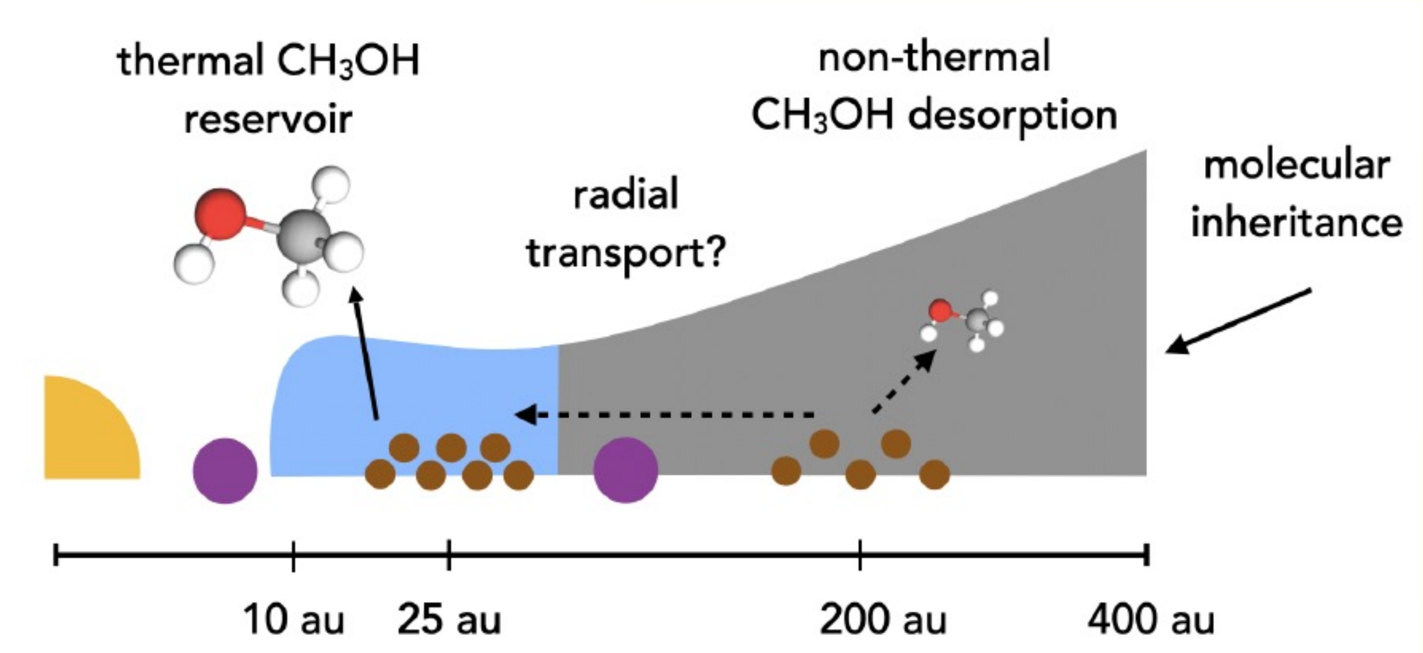


VLA HH212

Hoare et al 2015

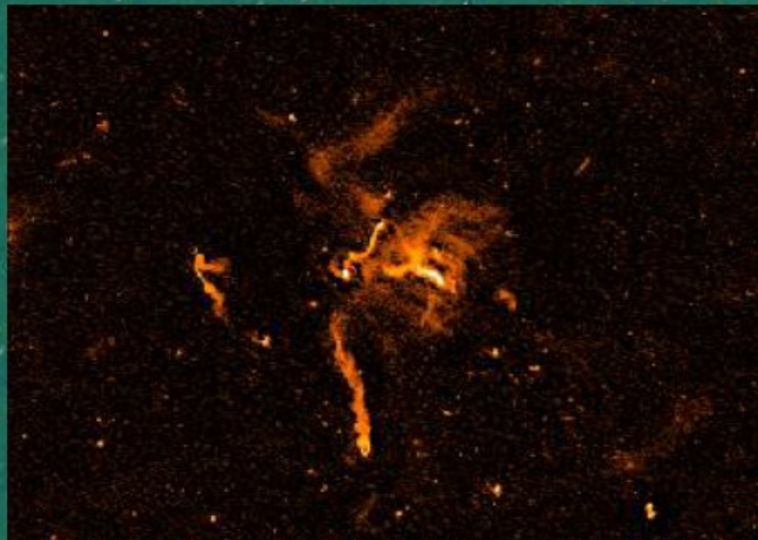
CH_3OH detected in protoplanetary disks

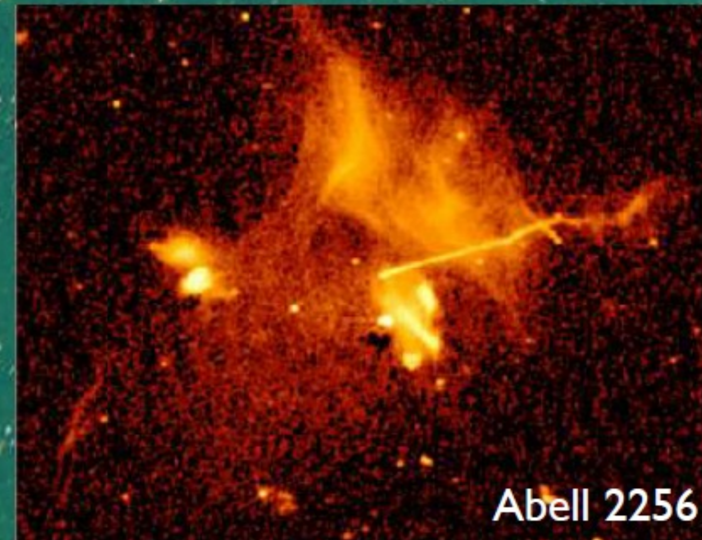
Comes from hydrogenation of CO on icy grains



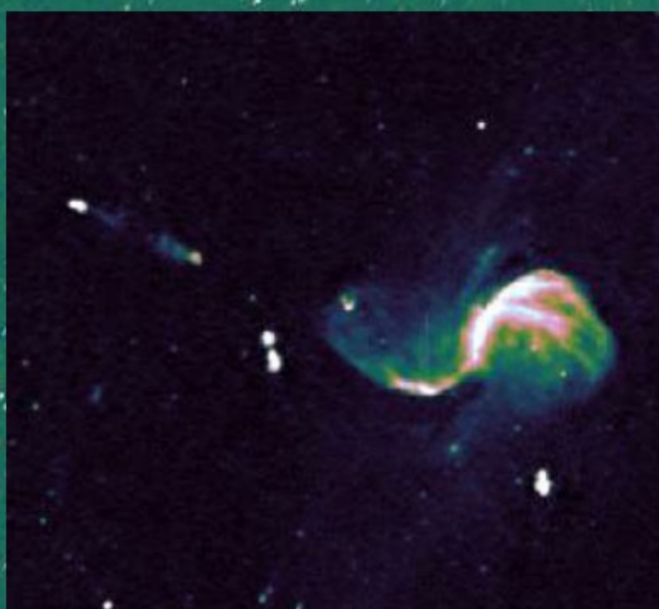
Detected with ALMA in HD 100546 disk (Booth, A et al 2021)

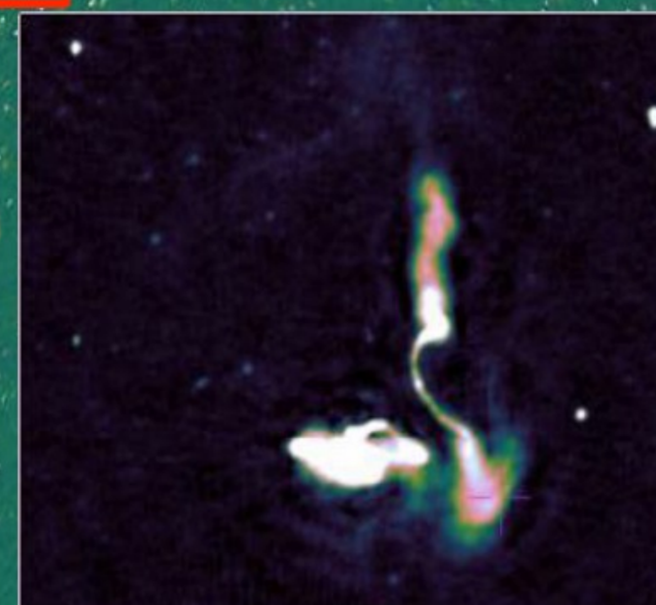
Key COM to form amino acids
COM inherited from dark clouds are not destroyed by the disk formation



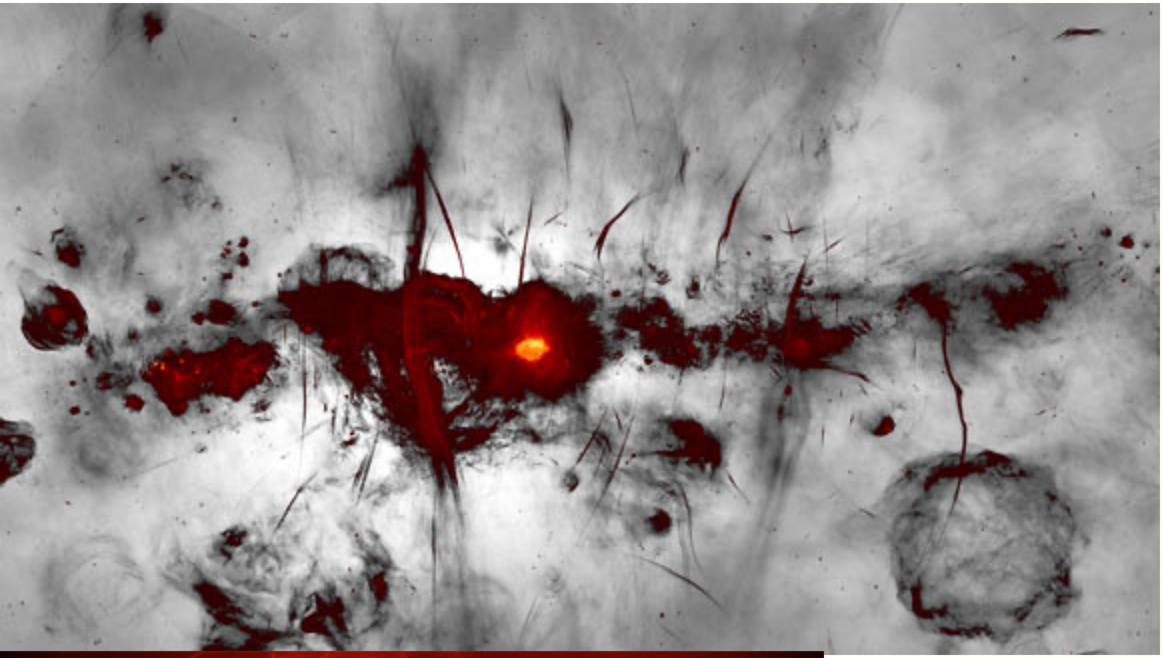


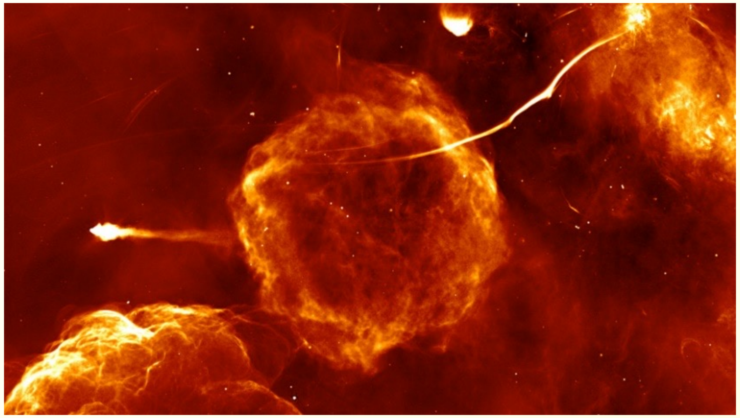
LOTSS: LOFAR 2m Sky Survey

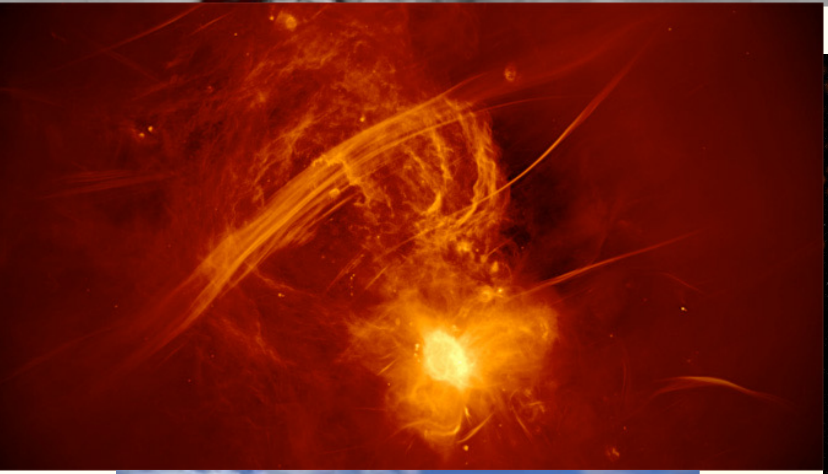


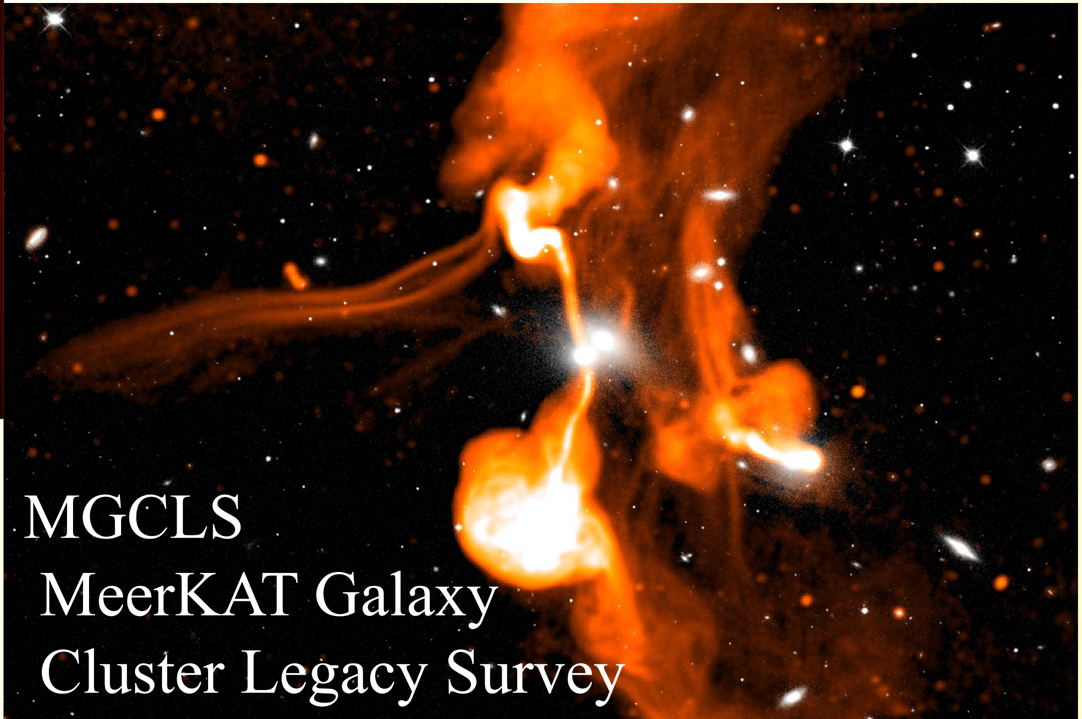


MeerKAT









In the next decades, we will know

What is dark matter and dark energy?
H_0 discrepancy solved?

EoR: how the first galaxies were born + JWST+ALMA

Pulsars: test new physics, gravity in strong field Gravitational waves

Nearby galaxies, high sensitivity, high resolution, dwarfs, UDG emission and absorption