SKA precursors

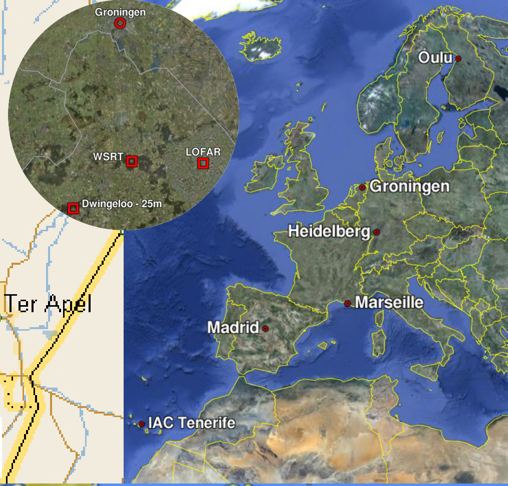
Albert Bosma

Laboratoire d'Astrophysique de Marseille

- why SKA ?
- some local history
- philosophy ...
- looking ahead in wonder ...

Foto P09997, Museum Boerhaave, Leiden
24/06/1970, opening WSRT, Johan Degewij


N380
Oosterwolde
Bovensmilde
Assen
Rolde
N33
Gasselternijveen
N378
Stadskanaal
N351
Appelscha
N E T H E R L A N D S
Hondsrug
Nieuw-Buinen
ASTRON
Locatie Westerbork
Boswachterij
Appelscha
Smilde
Mussel
N379
Nationaal Park
Drents-Friese Woud
B e n e l u x
Hooghalen
Borger
Tweede
Exloërmond
N374
Noordwolde
Oude
Willem
E l l e r t s v e l d
ASTRON
Locatie Lofar core
N366
Ter Apel
ASTRON / JIVE
Locatie Dwingeloo
Beilen
Westerbork
Nieuw-Weerdinge
Schoonoord
N364
Dwingeloo
Eursinge
N855
DRENTHE
N376
Emmer-Compascuum
N381
Nationaal Park


Groningen
WSRT
LOFAR
Dwingeloo - 25m
Oulu
Groningen
Heidelberg
Marseille
Madrid
IAC Tenerife


Groningen
Leiden
Marseille
JVLA
New York
FAST
ALMA
MeerKAT
ASKAP
Canberra

SKA key decisions sofar : headquarters near Manchester, UK

	Australia	**South Africa**
Phase 1	SKA_1 low frequency sparse aperture array SKA_1 mid frequency dish array with phased array feeds (PAF) incl. ASKAP	SKA_1 mid frequency dish array with single pixel feed incl. MeerKAT
Phase 2	SKA_2 low frequency sparse aperture array	SKA_2 mid/high frequency dish array with single pixel feed SKA_2 mid frequency dense aperture array

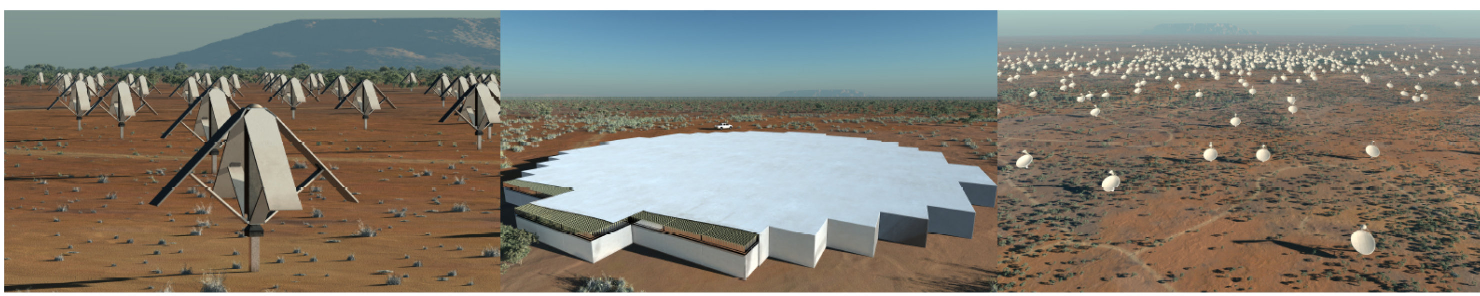


Figure VII: The three different antenna types ("radio wave receptors") of the SKA. From left to right: sparse aperture array (low: 70 – 500 MHz) used in SKA Phase 1 & 2 , dense aperture array (mid: 500 – 1000 MHz) used in SKA Phase 2 only, and high frequency dishes (high: 500 MHz – [3 GHz SKA_1] 10 GHz) used in SKA Phase 1 & 2. Note that the frequency ranges and in particular the edge frequencies of each band will vary in the design process. (Image credits: see page 136)

SKA key science areas: Carilli et al. 2004 will be updated

Probing the dark ages

- Mapping out redshifted neutral hydrogen (H I) from the epoch of reionisation (EoR)

Galaxy Evolution, Cosmology and Dark Energy

- Dark energy via baryonic oscillations traced by the 3-d galaxy distribution in the Universe
- Galaxy evolution as a function of cosmic time (H I observations in emission and absorption)

Strong Field Tests of Gravity

- Tests of theories of gravity via binary pulsars with neutron star and black hole companions
- Detection of nano-Hertz gravitational radiation using pulsar timing arrays

The Origin and Evolution of Cosmic Magnetism

- The rotation measurement grid

The Cradle of Life will investigate all aspects of astrobiology.

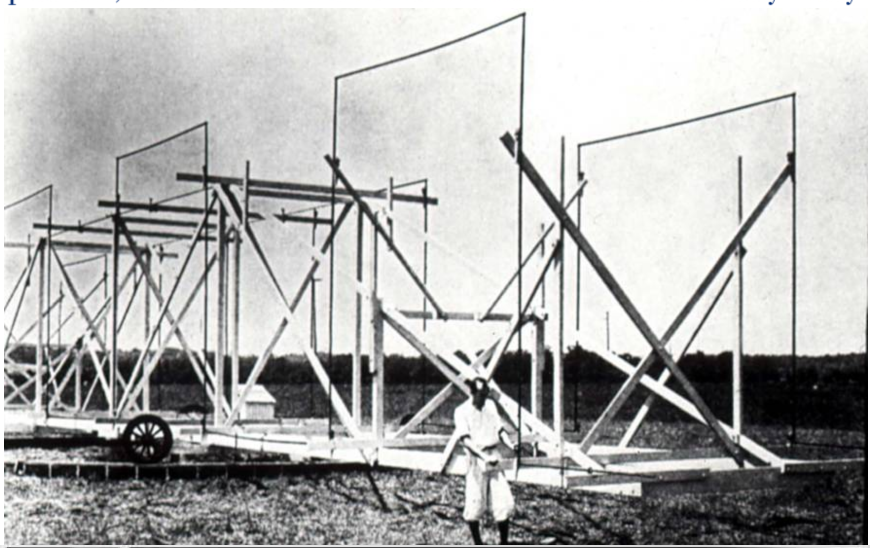
- Planet formation in proto-planetary disks

Exploration of the Unknown

Variations of these science areas can be found in the Key Science Projects of the various SKA precursors…

Exploration of the unknown : spirit of discovery

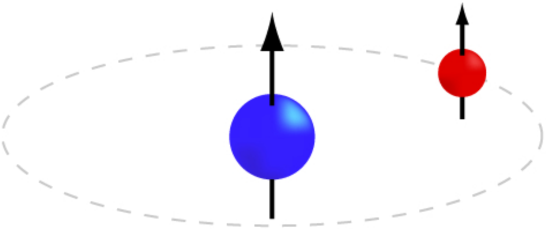
In the early 1930s, Karl Jansky investigated radio interference in transatlantic telephone links and, in the process, discovered radio emissions from the Milky Way



It was Grote Reber, however, who decided that this was an important new way of studying the Universe and decided to take some action. He said, “I consulted with myself and decided to build a dish!"

Reber (1940) was picked up by a “classical” astronomer – Oort

Van de Hulst (1957, IAU 4, 3)



One λ = 21 *cm photon is emitted when the spins flip from parallel to antiparallel.*

The subject of the 21-cm. line needs no introduction to this audience. Perhaps as an introduction I may mention one moment that belongs to the pre-history of the investigations of this line. In the spring of 1944 Oort said to me: ‘We should have a colloquium on the paper by Reber; would you like to study it? And, by the way, radio astronomy can really become very important if there were at least one line in the radio spectrum. Then we can use the method of differential galactic rotation as we do in optical astronomy.’

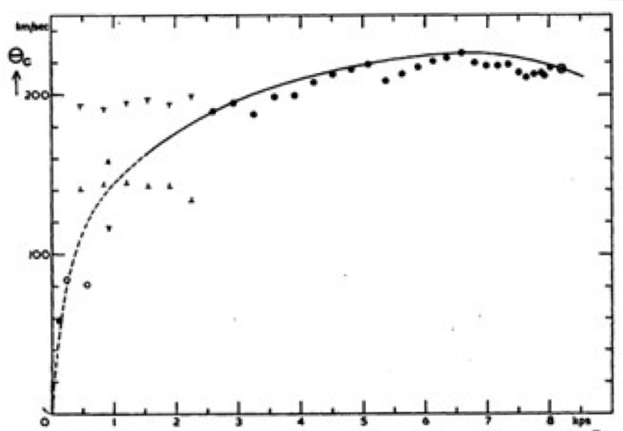
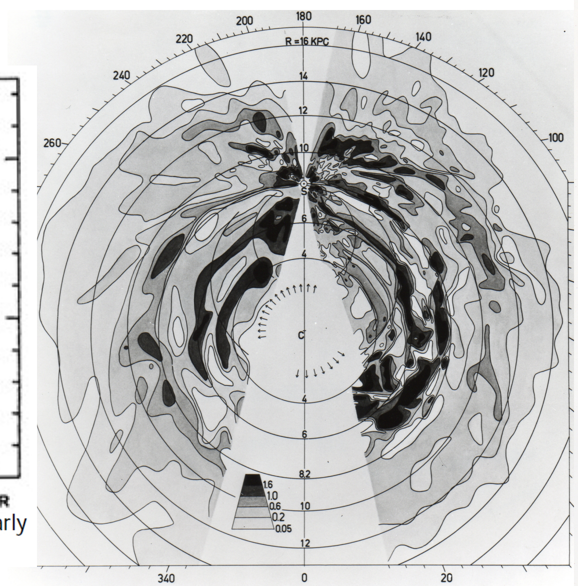
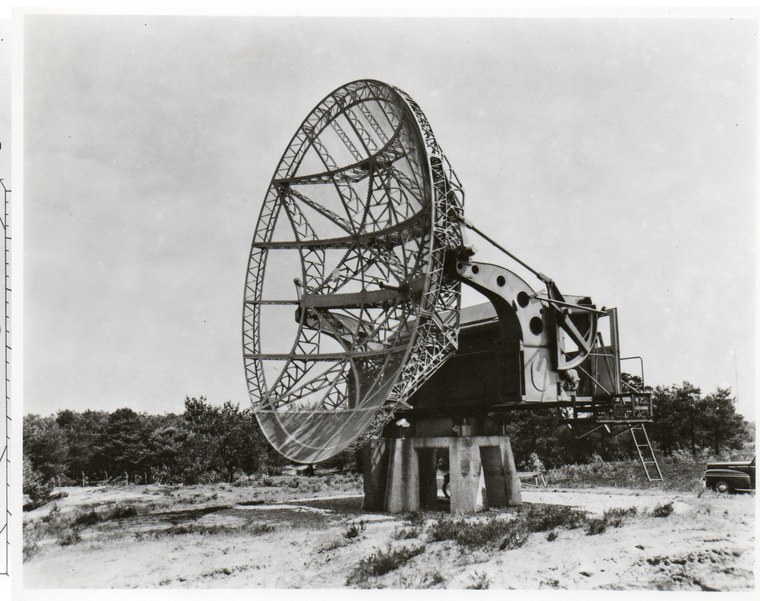
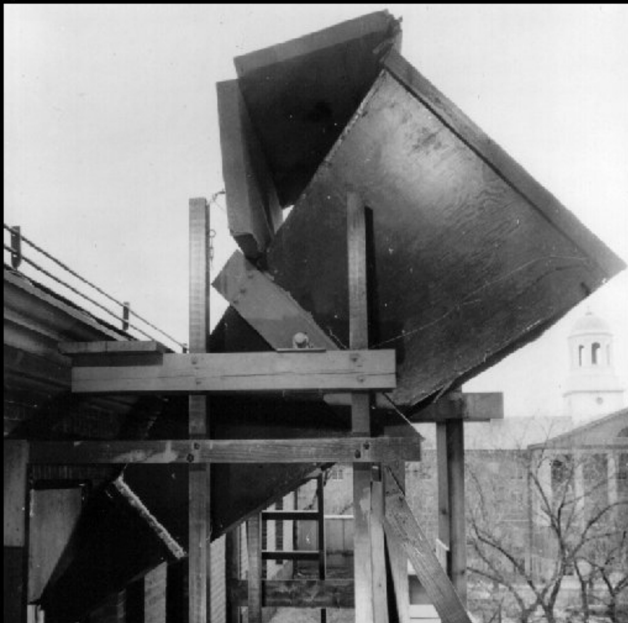


Figure 10: First rotation curve of the Galaxy, which is nearly flat from 3-8 kpc (after Kwee et al., 1954: 219).







Ewen with his equipment at Harvard

No follow-up!

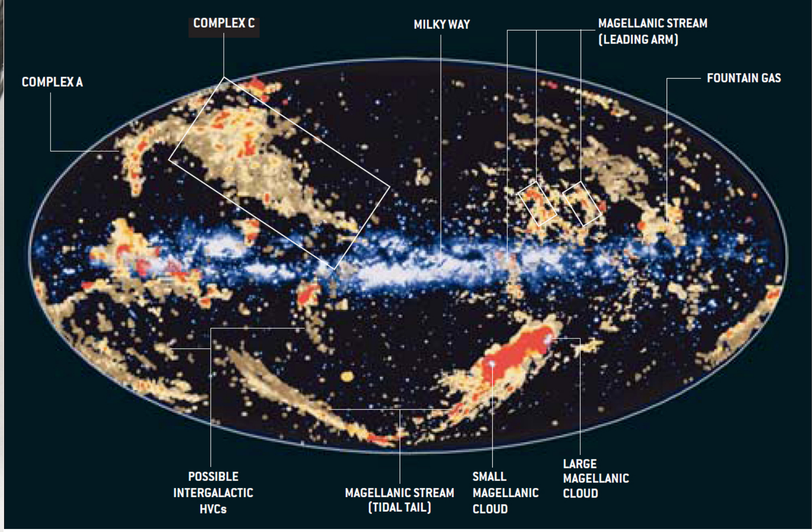
Henk van de Hulst was lecturing there

THE SPIRAL STRUCTURE OF THE OUTER PART OF THE GALACTIC SYSTEM DERIVED FROM THE HYDROGEN EMISSION AT 21 cm WAVE LENGTH

BY H. C. VAN DE HULST, C. A. MULLER AND J. H. OORT

The writers recall with pleasure the valuable information and friendly co-operation received from Drs EWEN and PURCELL, and from Dr F. KERR, who was our liaison with the Australian group. A similar co-operation has continued among all workers in this field; one of its results is the exchange of a regular "1420 Mc/s newsletter", edited at Leiden.

Purcell got the 1952 Nobel prize for Physics, with Felix Bloch, for Nuclear Magnetic Resonance in liquids and solids



MAP OF GALACTIC GAS combines radio observations of neutral hydrogen (*colored splotches*) with a visible-light image of the Milky Way (*white*). The map depicts our sky, reprojected so that the galactic disk runs across the middle; the core of the galaxy lies at the center. High-velocity clouds of hydrogen, such as complexes A and C, are located above and below the disk.

HVC's & spiral structure

Wakker & van Woerden 1997; Dame & Thaddeus 2011

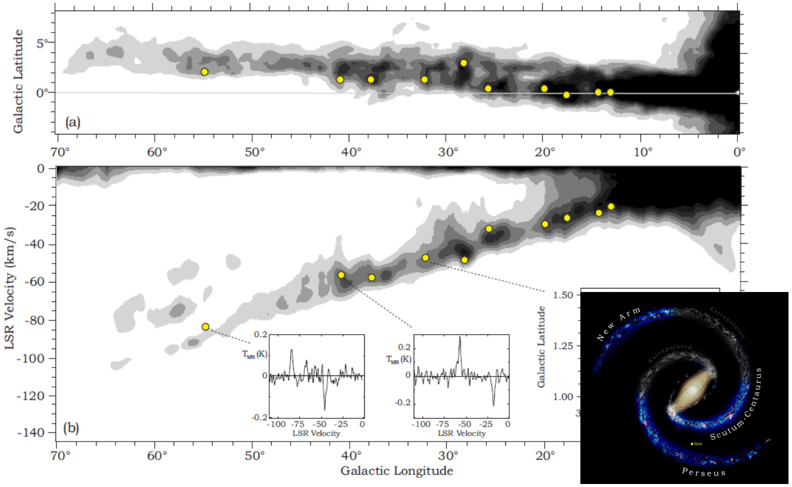
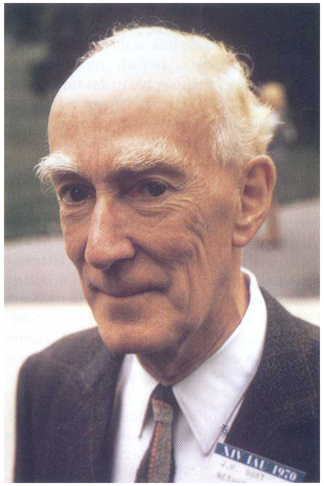


Fig. 3.— (a) Velocity-integrated 21 cm emission from the new arm, obtained by integrating the LAB survey over a window 14 km s^{-1} wide that follows the arm in velocity. The window is centered on the lower dashed line shown in both panels of Fig. 1, defined by the equation $v = -1.6 * l$. The grayscale levels run from 100 K km s^{-1} (*light gray*) to 600 K km s^{-1} (*black*). (b) Longitude-velocity diagram of 21 cm emission from the new arm, obtained by integrating the LAB survey over a window 3.5° wide that follows the arm in latitude. The

WSRT - unexpected results - Oort

Oort 1961: 10 page justification => 1970 WSRT => Strom (1995)



The importance of such observations for our understanding of the mechanism of spiral structure can hardly be over-estimated. They would, for instance, give information on the systematic radial components of the motion of the gas in the arms.

OORT'S DREAM (1961)

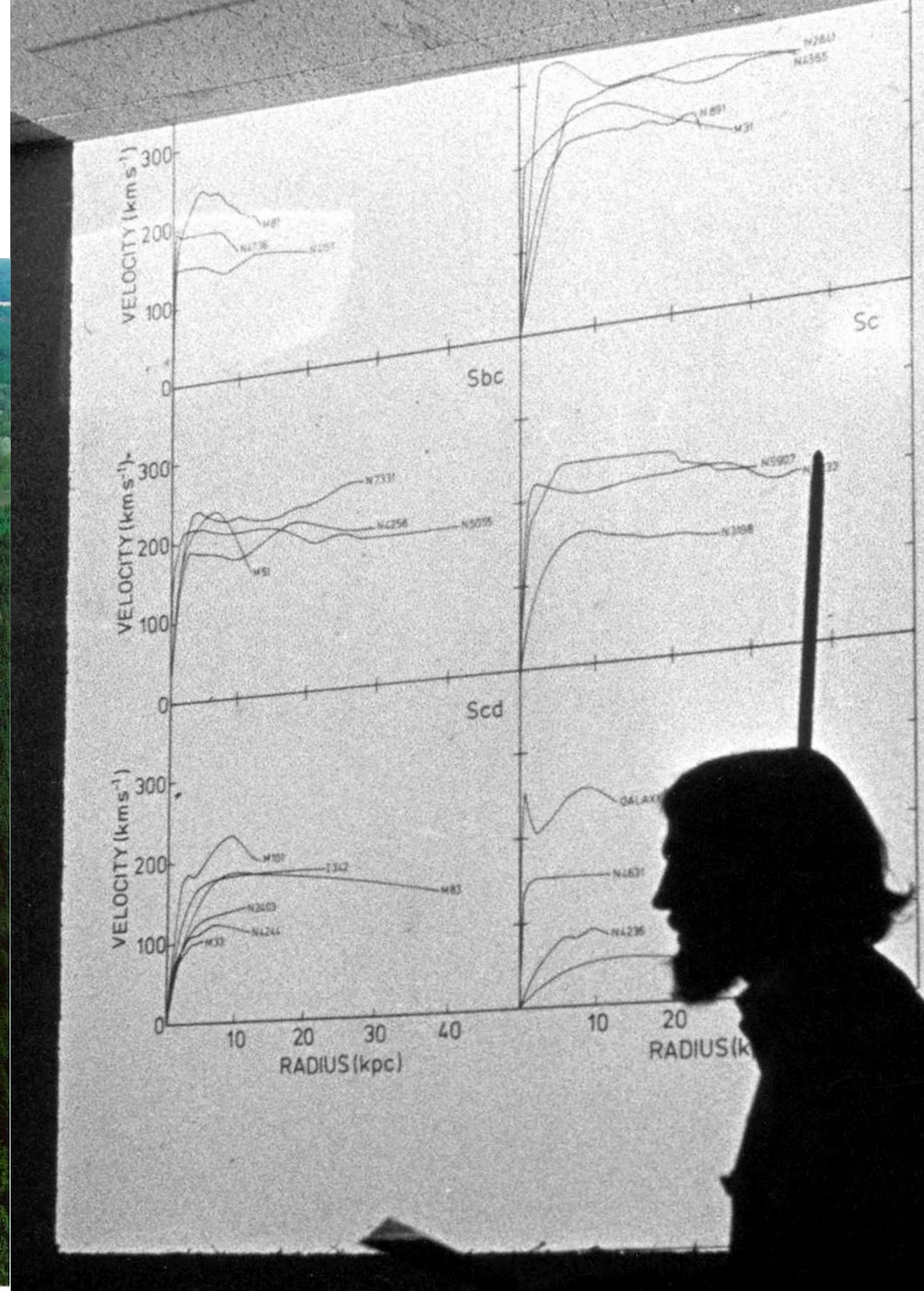
21-cm Radiation from More Distant Galaxies
Measures of total hydrogen content and rough data on rotation will be obtainable for something of the order of 1,000 galaxies.

Strom 1995 25 YEARS OF TUNING IN TO THE COSMOS

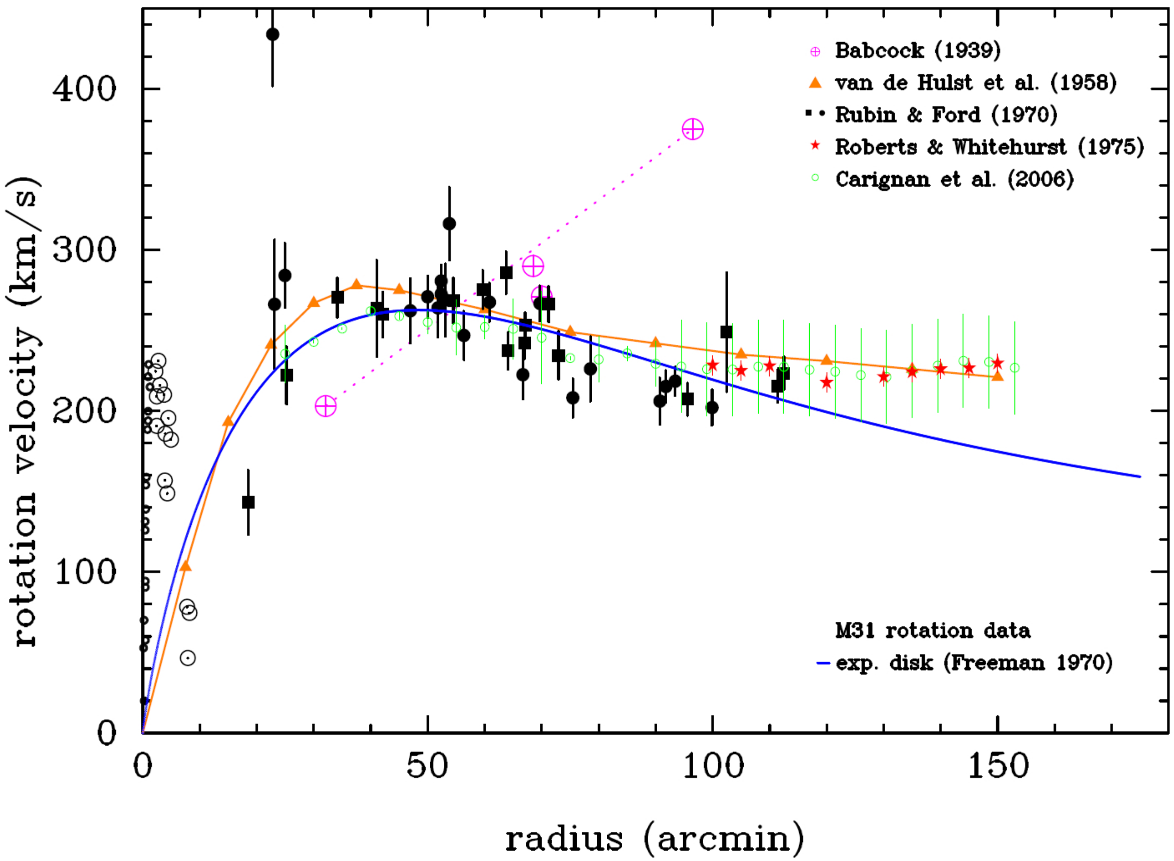
One of the most stunning discoveries made with the WSRT arose from just such a careful study of galaxy rotation.

What was in fact observed was that while the rotation rate did not continue its rapid increase, it also did not decline (Bosma 1978). This can be clearly seen in NGC 3198 (Figs. 4 and 5). In most other galaxies as well, the

NGC 5055, a “dull” galaxy : HI much larger than optical



M31 – Need for dark matter based on radio data



Local Group 'timing' argument

Kahn & Woltjer 1959

M31 approaches MW with speed 125 km/s

M31 and MW orbit around center of mass

M* ≥ 1.8 10**12 M⊙

likely intergalactic gas (high T, low ρ) [?!]

HI rotation curves beyond the optical image

Bosma, 1978, 1981a,b

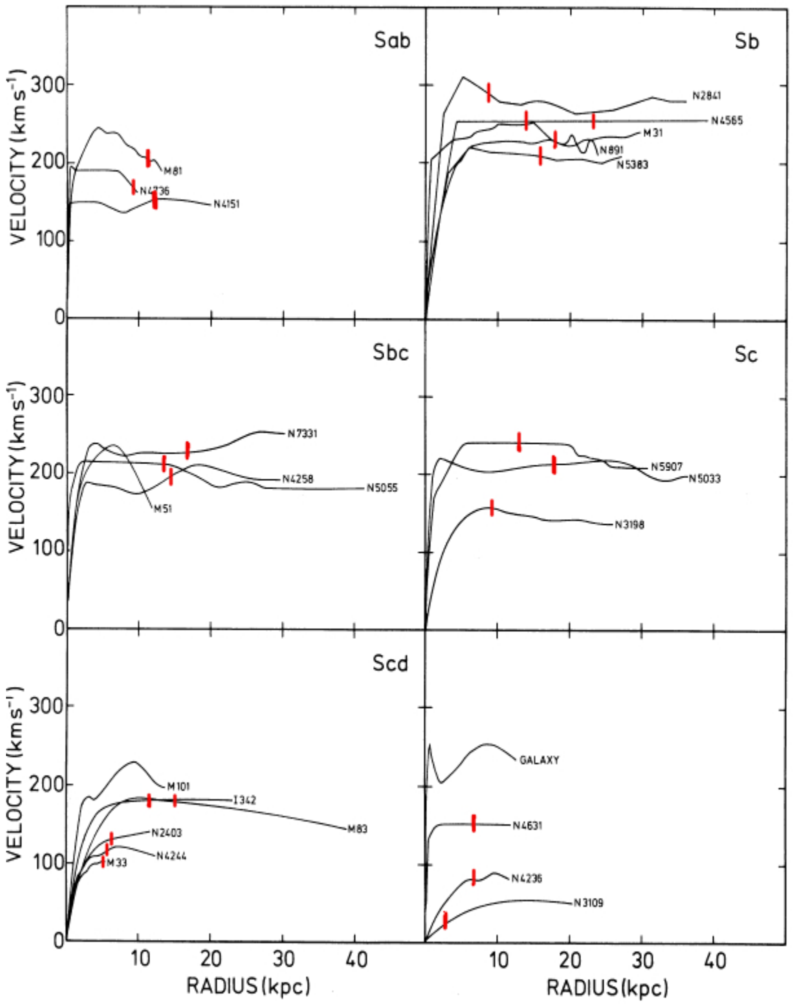
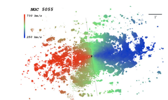
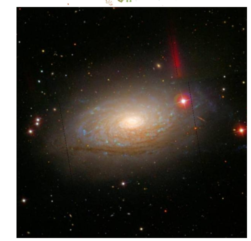


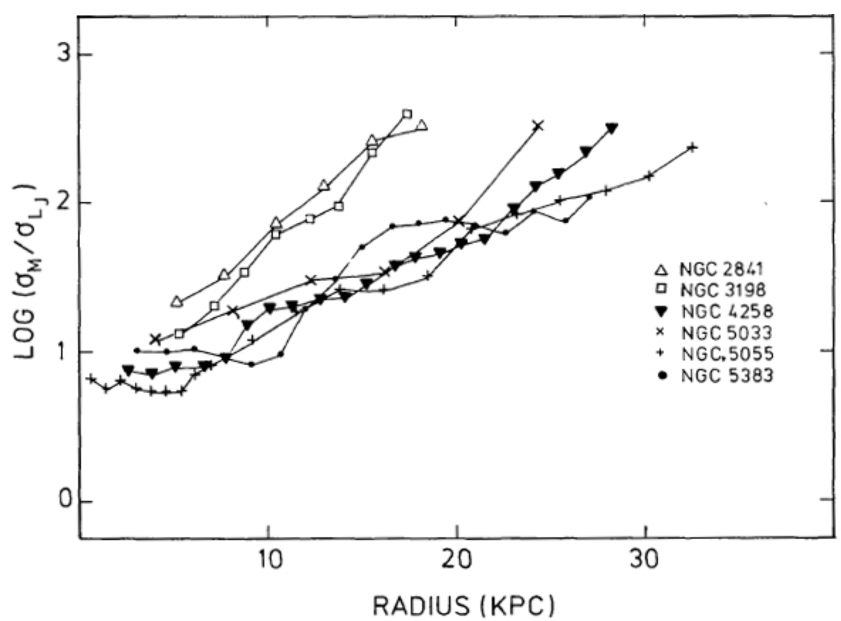
FIG. 3. Rotation curves of 25 galaxies of various Hubble types.





$V_{obs} = V_{sys} + V_{\theta} \sin i \cos\theta + V_R \sin i \sin\theta$

Van der Kruit & Allen, ARAA 16, 103 (1978)

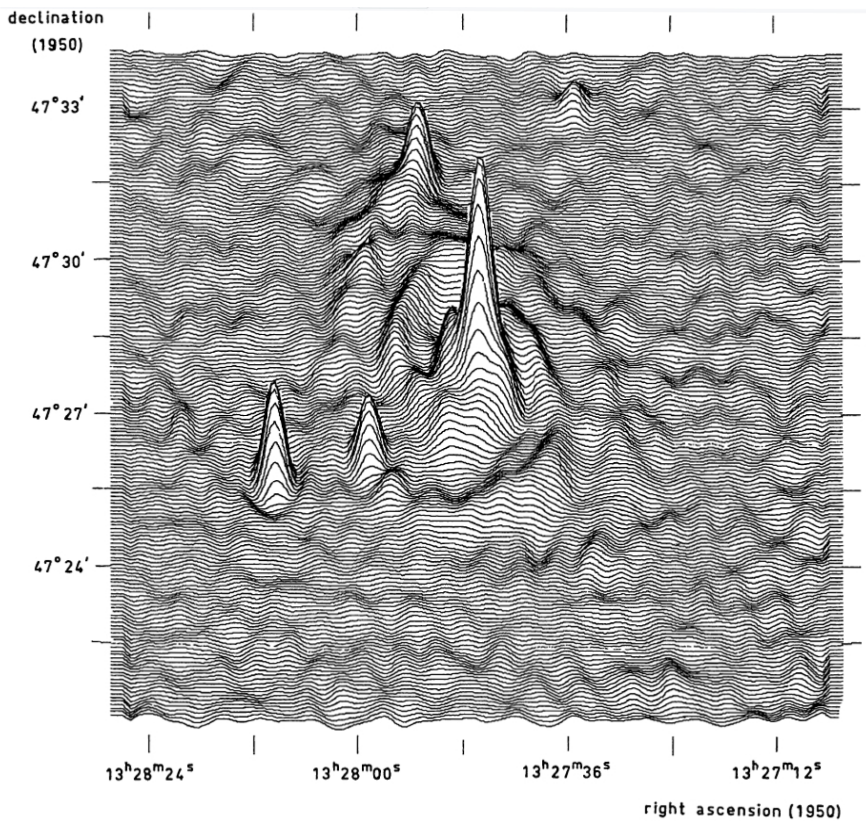


Bosma 1978, Bosma & Van der Kruit 1979

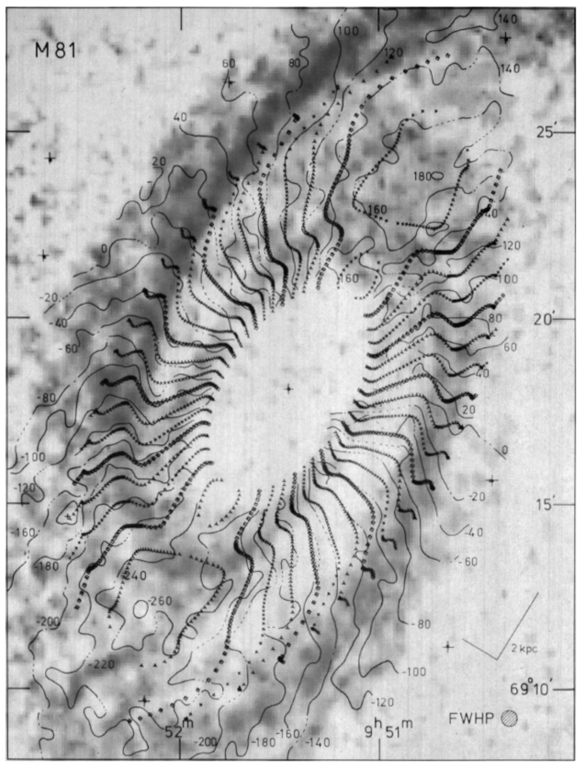
What was expected, and why did I observe these galaxies ?

- basically to get rotation curves to "test the density wave theory"
- however, spiral structure is "icing on the cake", and thus more
  useful if the icing tells you something about the cake …
- this was used later: Athanassoula et al. (1987), see also Bosma (1998)

The WSRT was built for doing cosmology with radio sources & M31 in HI



Mathewson, van der Kruit & Brouw, 1972



Visser 1980 + Rots & Shane 1975

SERENDIPITOUS DISCOVERIES IN RADIO ASTRONOMY

Proceedings of a Workshop held at the National Radio Astronomy Observatory Green Bank, West Virginia on May 4, 5, 6, 1983

Lots of discoveries in radio astronomy were/are NOT planned
- then, how did they come about ?
- what spirit is necessary to make them ?
- "exploration of the unknown", what is meant by this ??
- use a telescope, built for some purpose, for something new

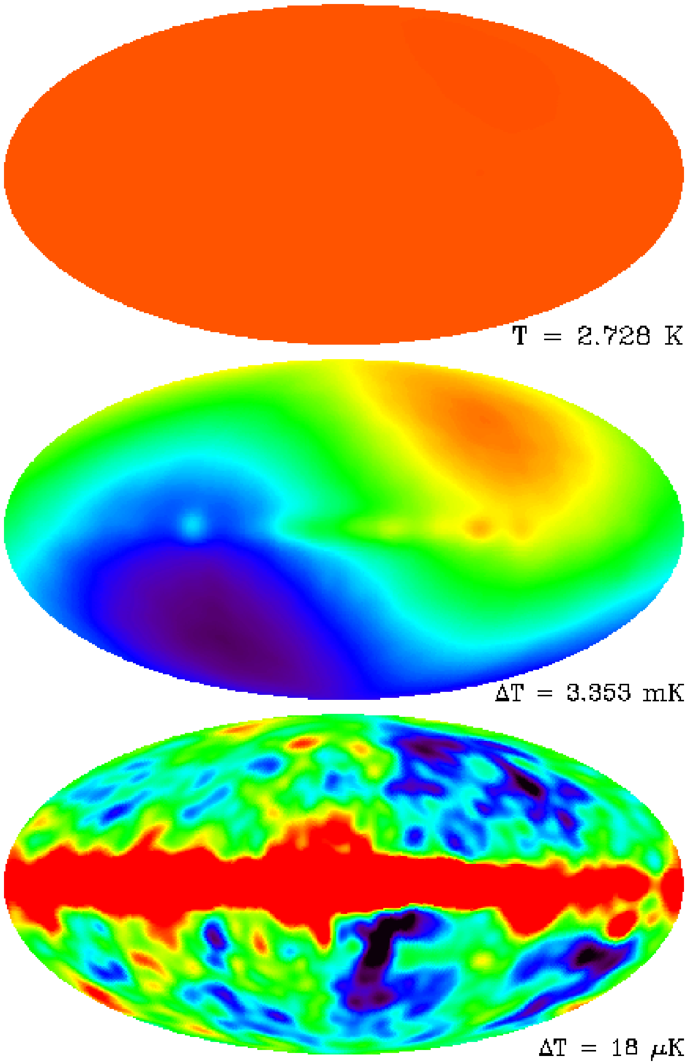
A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

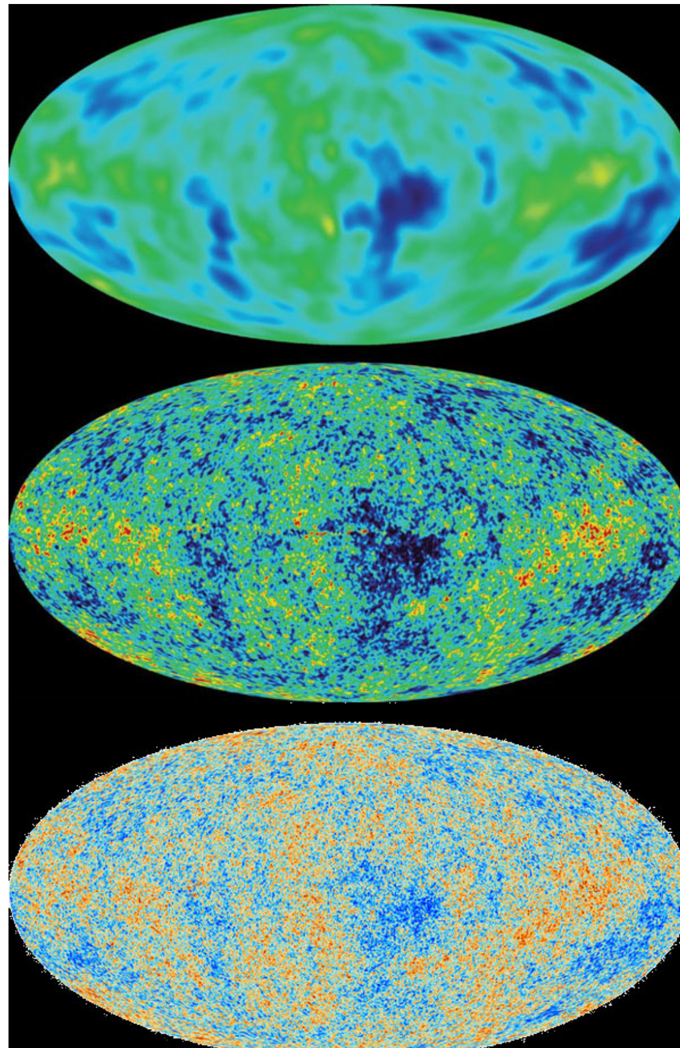
ApJ 142, 419-421, 1965

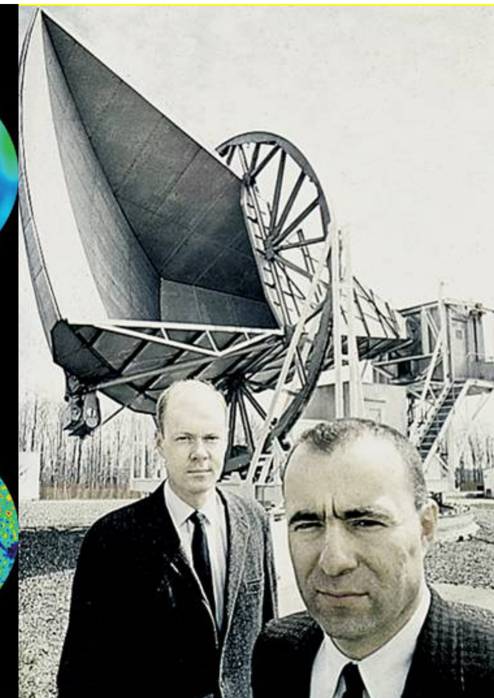
May 13, 1965

BELL TELEPHONE LABORATORIES, INC
CRAWFORD HILL, HOLMDEL, NEW JERSEY

A. A. PENZIAS
R. W. WILSON





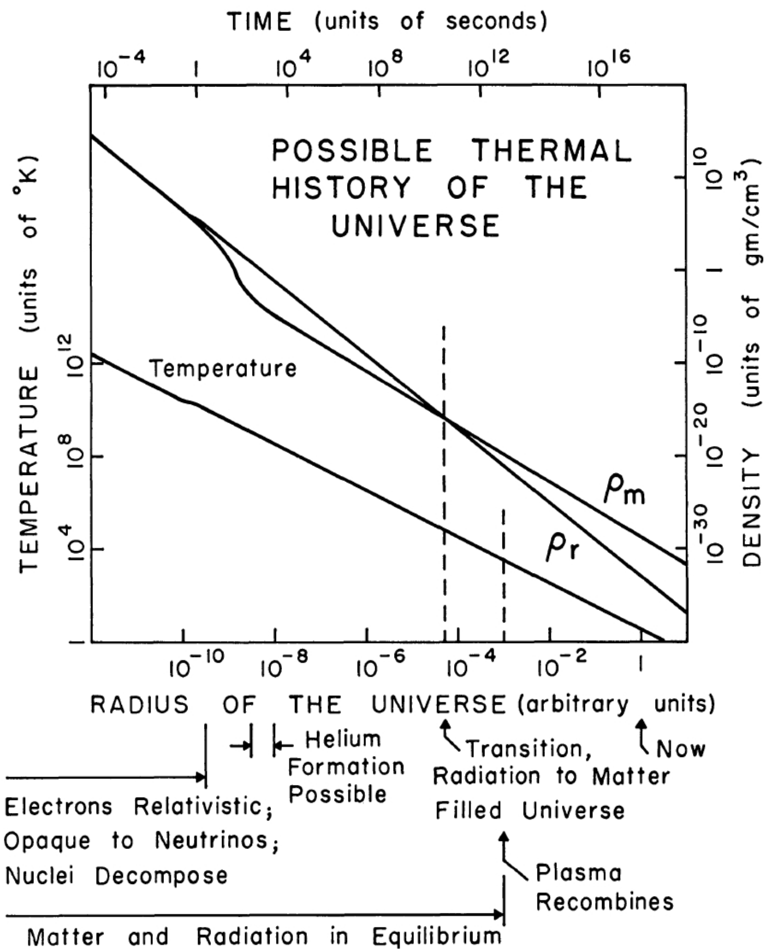


Even though Penzias & Wilson stumbled upon the CMB, the neighbours in Princeton had a research programme...

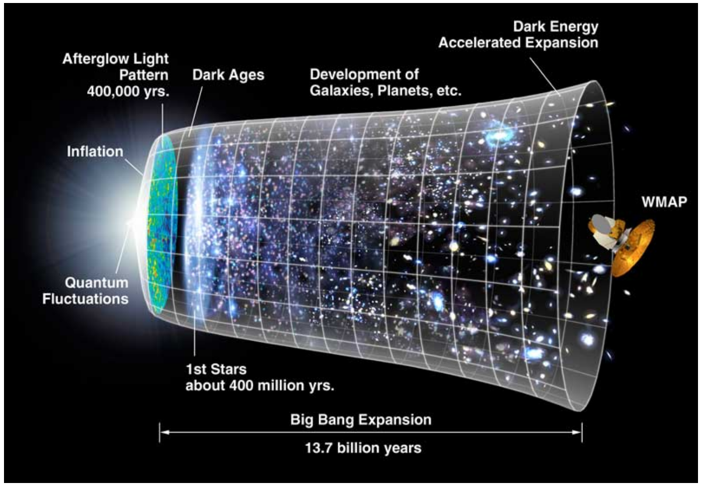
COSMIC BLACK-BODY RADIATION

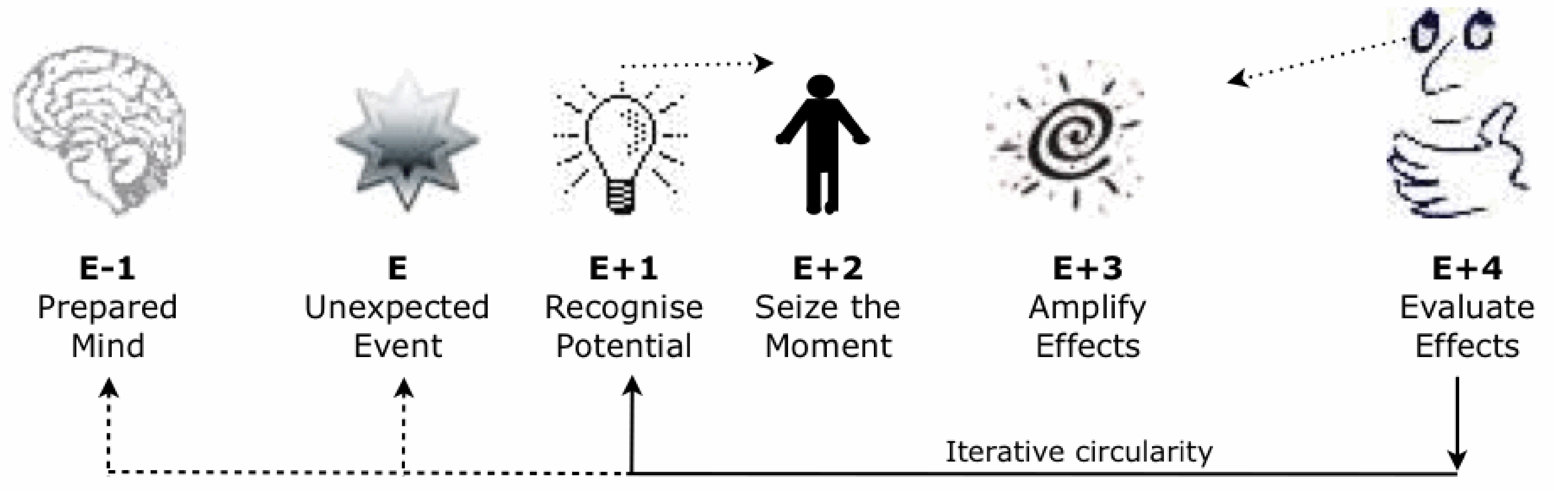
R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson

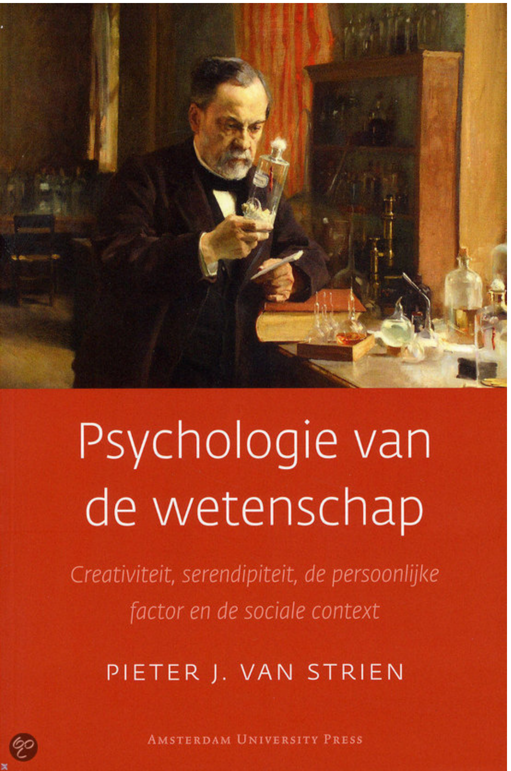
May 7, 1965
Palmer Physical Laboratory
Princeton, New Jersey



redoing in part work of
Alpher et al. 1948, 1953





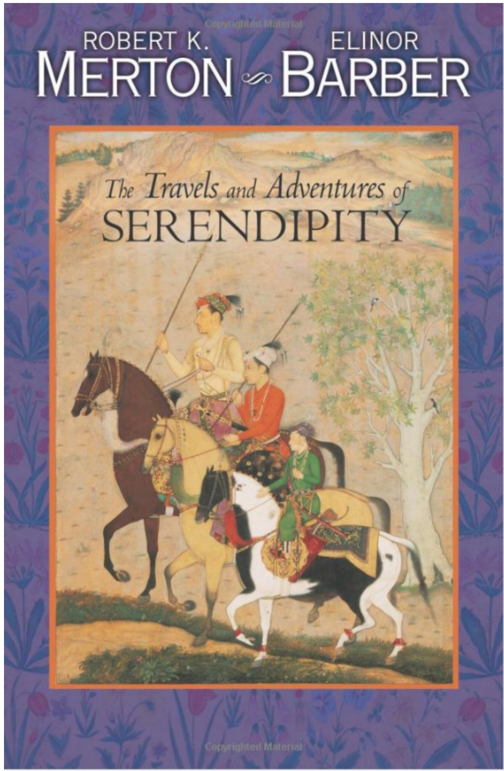


Your "hey, that's funny" observation may fit into someone else's science programme ...

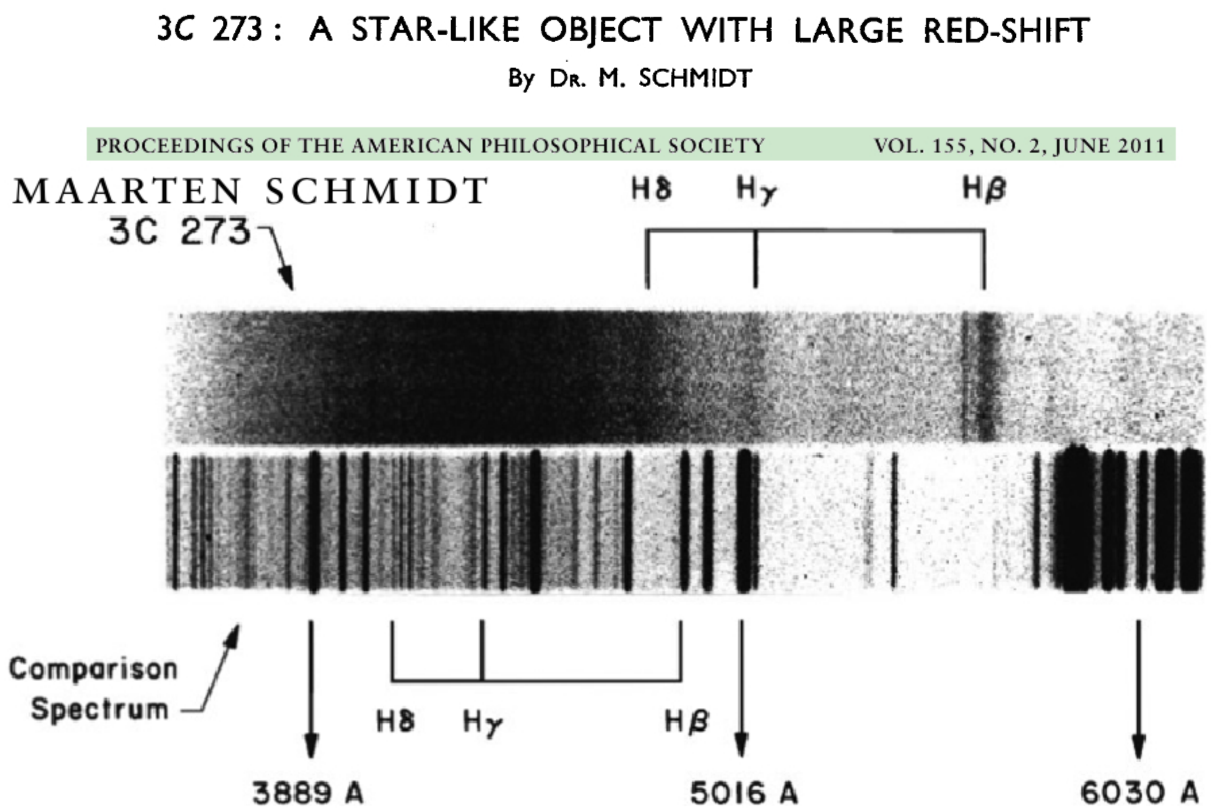
or start a new subject of research ...

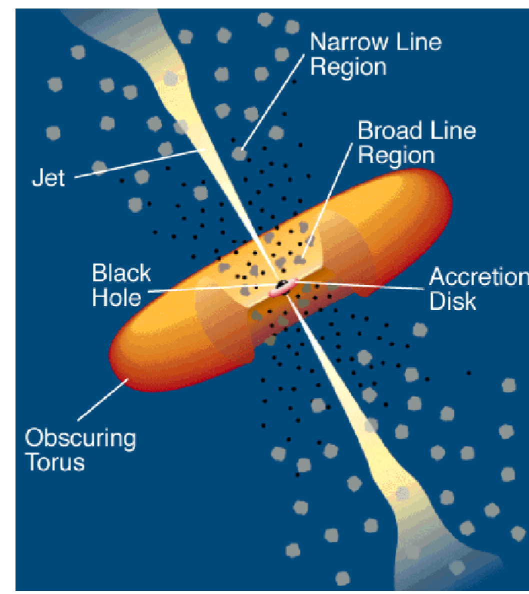
« La chance ne sourit qu'aux esprits bien préparés. »

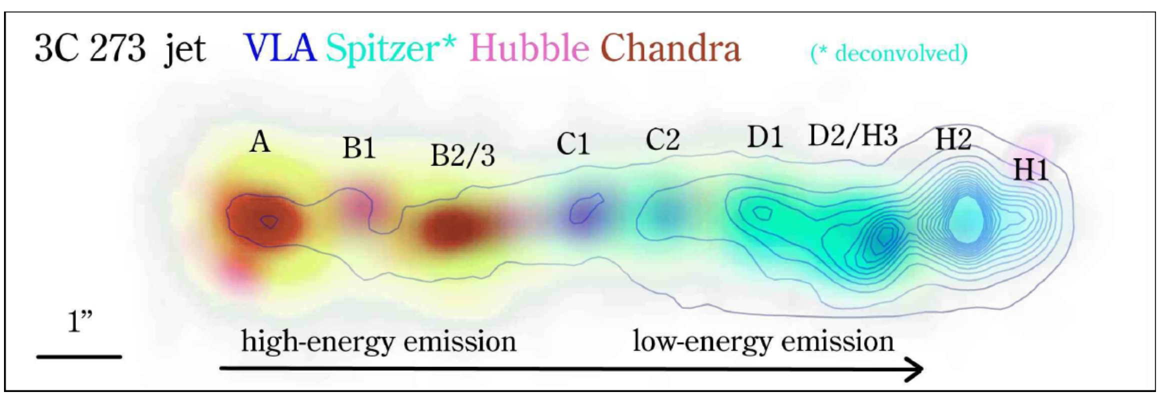
Louis Pasteur



Quasar discovery after accurate radio position

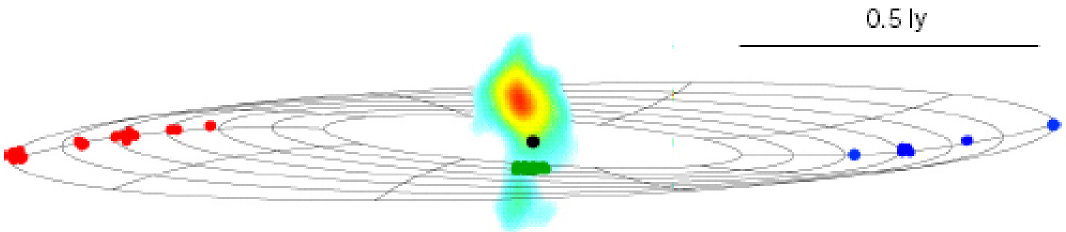




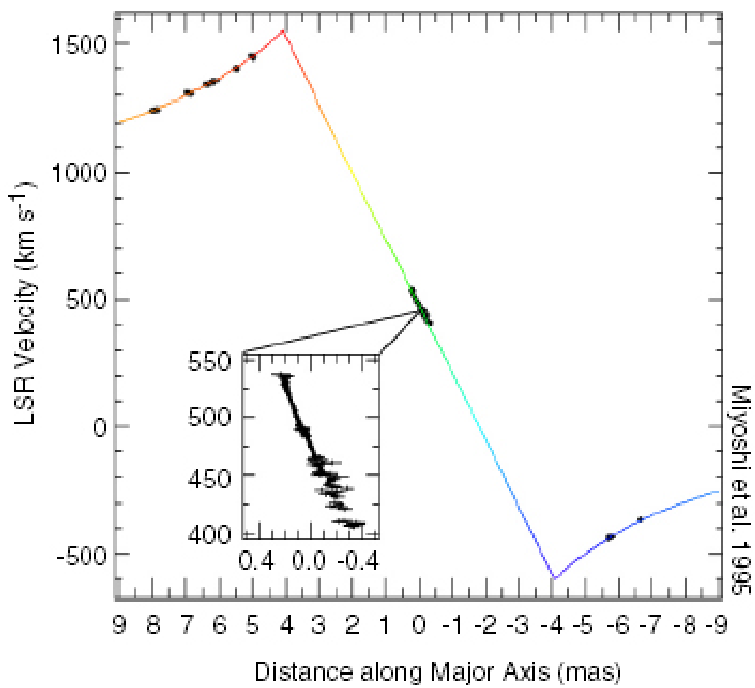


Galactic Nuclei as Collapsed Old Quasars

D. LYNDEN-BELL   Nature 223, 690, 1969



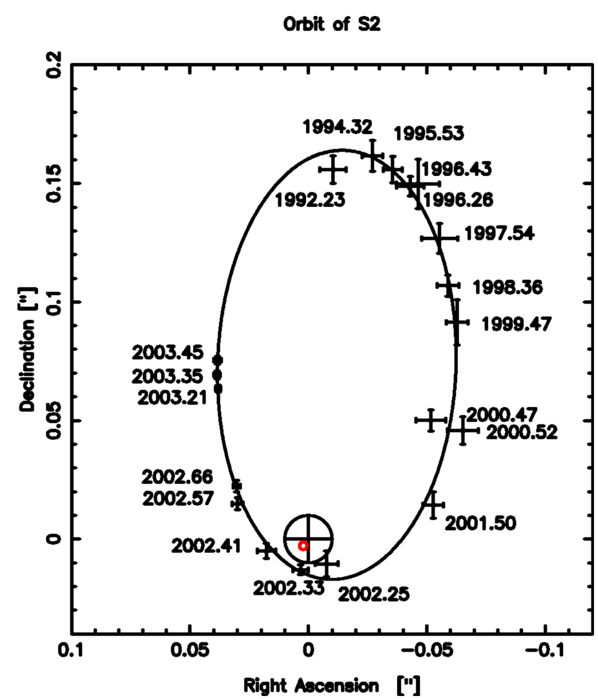
Based on Herrnstein, Greenhill et al. 1998

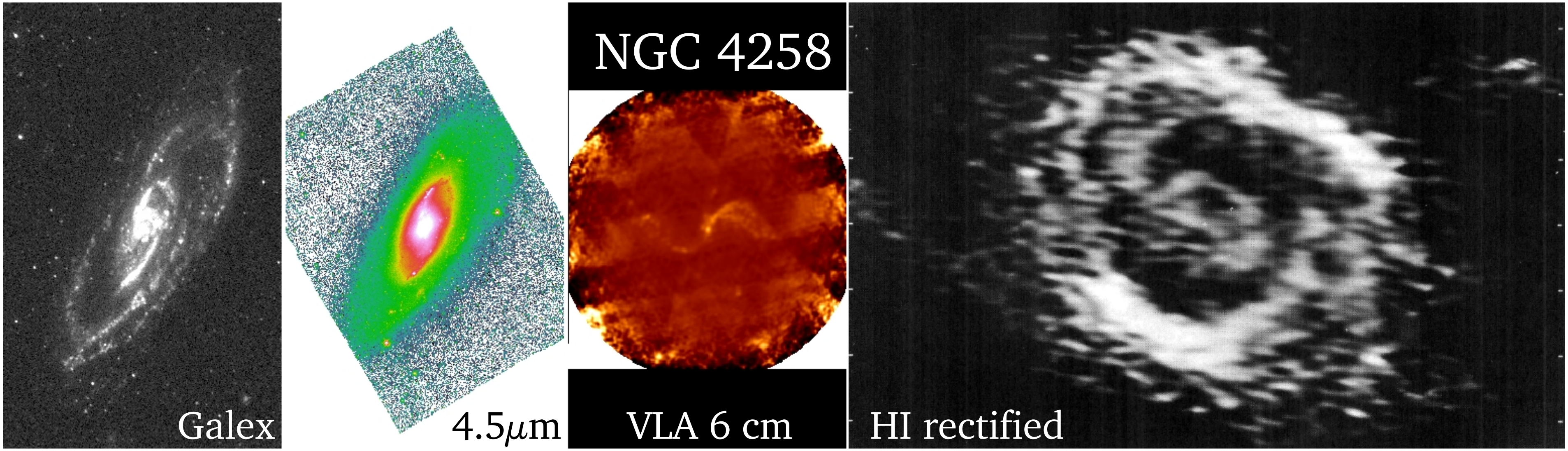


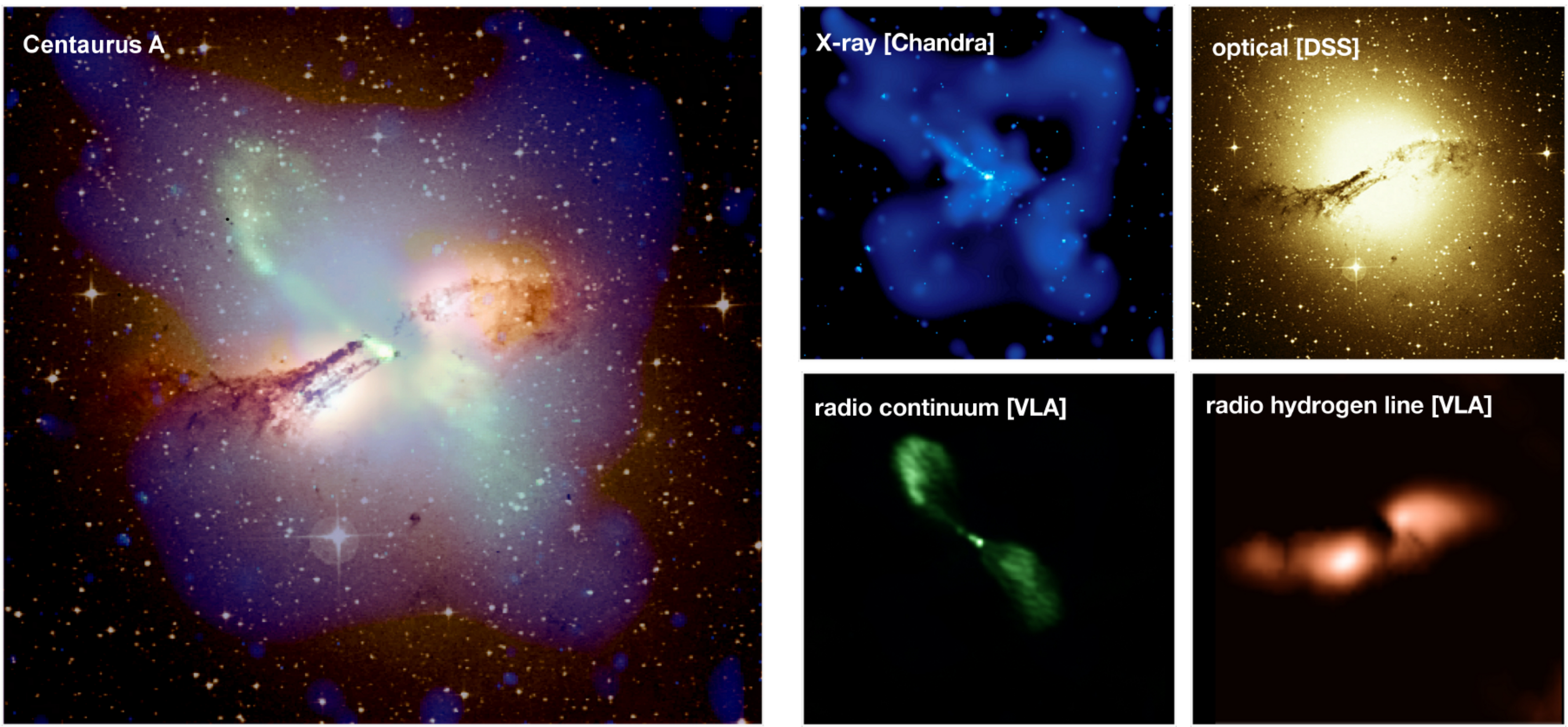
Arrangement : Greenhill

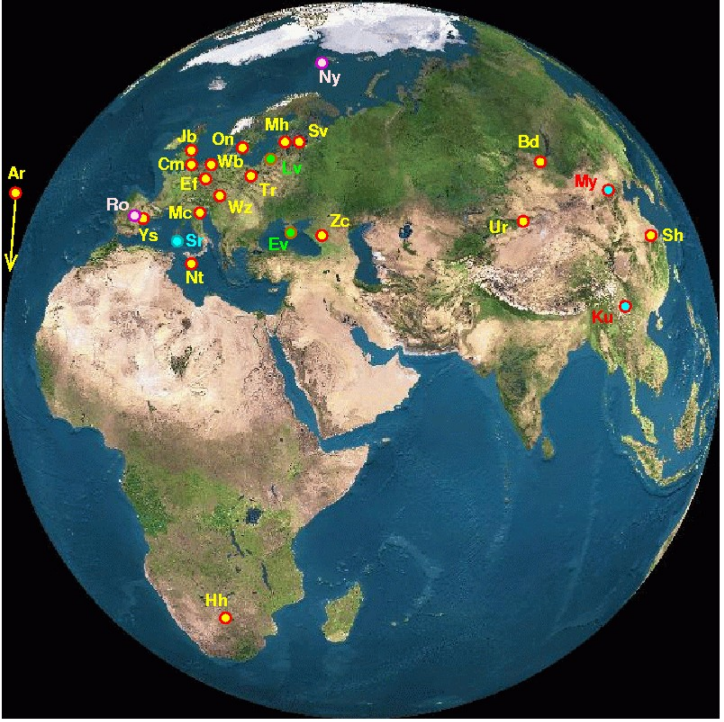
BH mass of NGC 4258 using masers, first by Miyoshi et al. 1995

Stars orbiting the Galactic Center BH
Genzel et al. ; Ghez et al.

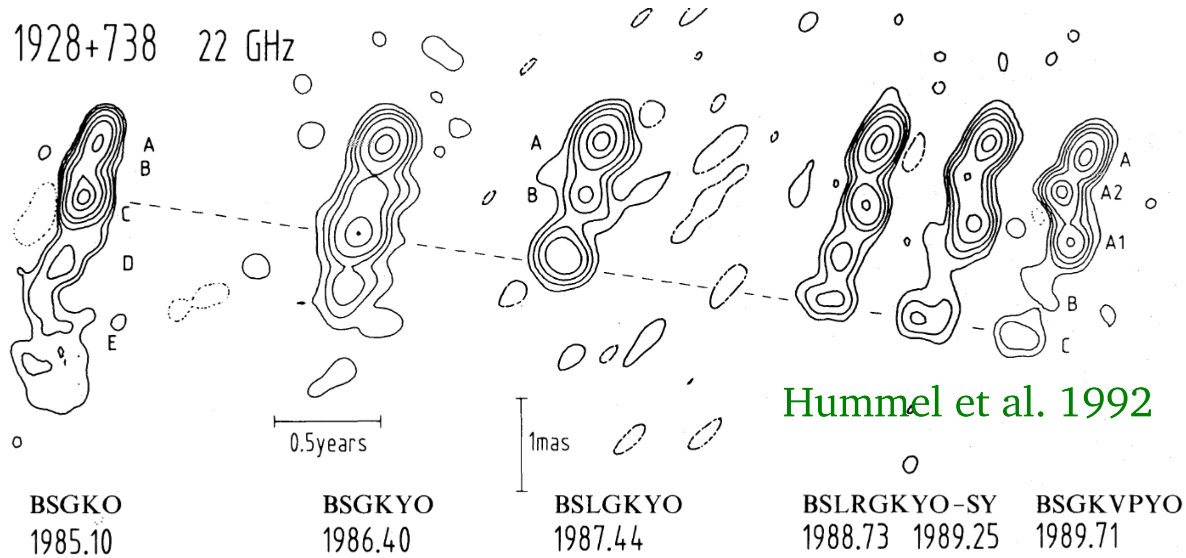



NGC 4258
Galex
4.5μm
VLA 6 cm
HI rectified


Centaurus A
X-ray [Chandra]
optical [DSS]
radio continuum [VLA]
radio hydrogen line [VLA]

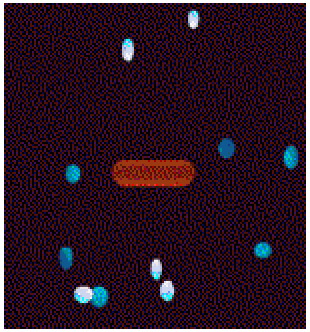
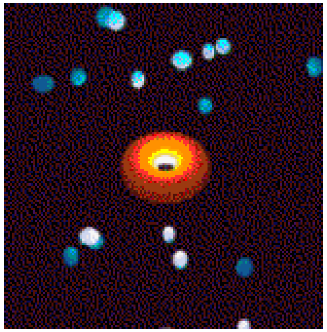
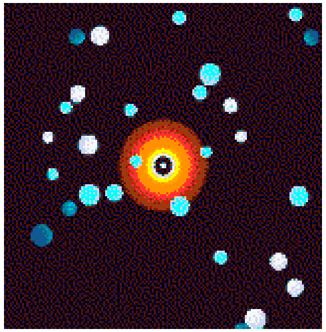
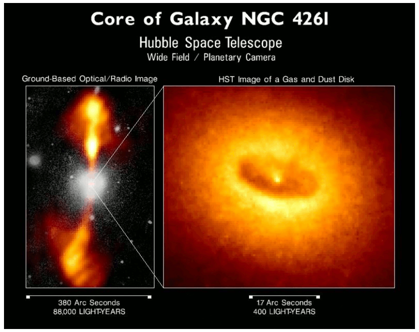


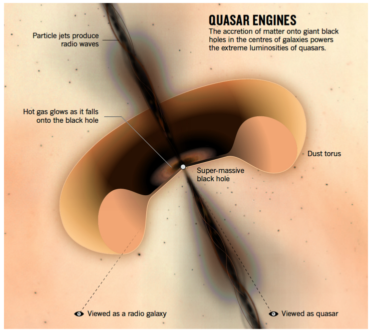
European VLBI Network, VLBA, Merlin, etc...



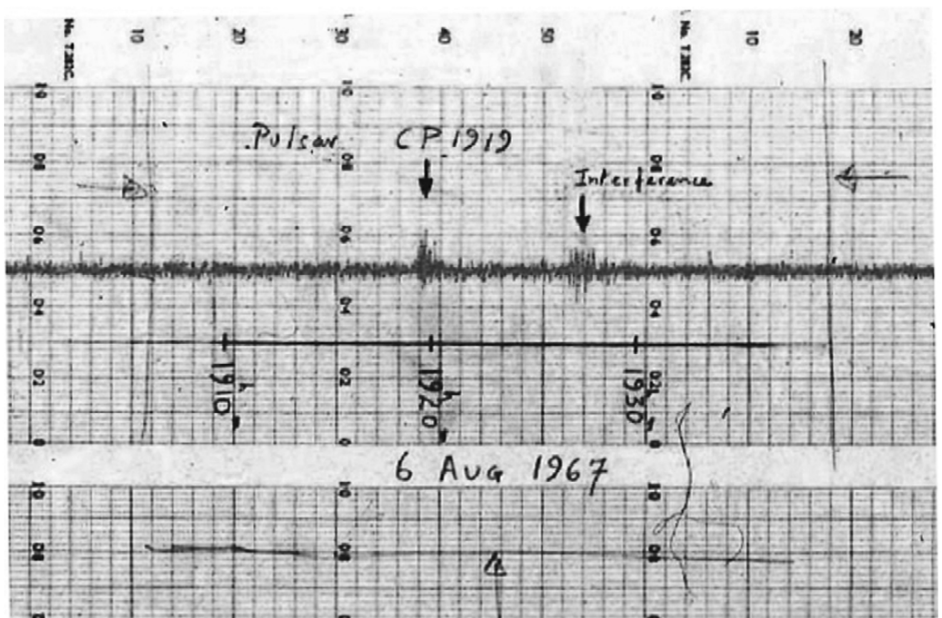
The Unified Model of AGN - Orientation of the Nucleus

Type 2 objects - Seyfert 2s, Narrow Line Radio Galaxies and Type 2 Quasars
Type 1 objects - Seyfert 1s, Broad Line Radio Galaxies and (Type 1) Quasars
Blazars - BL Lac Objects and Optically-Violent Variables

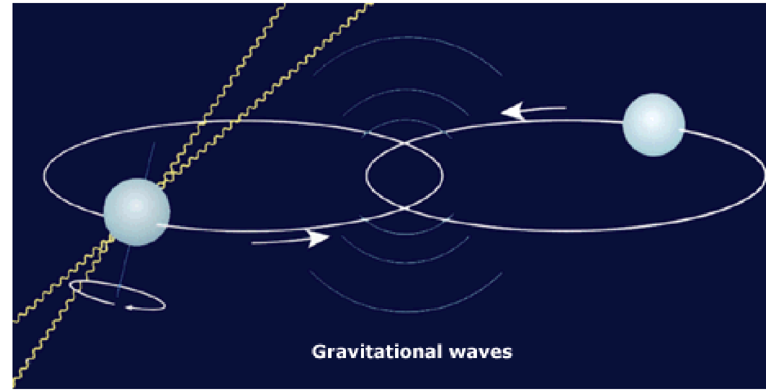





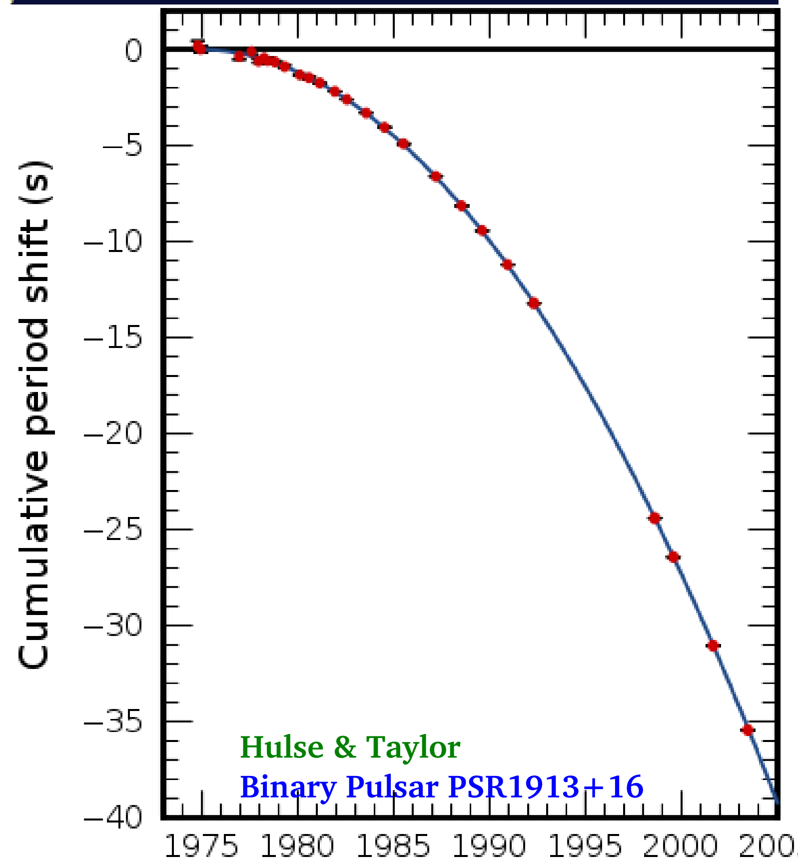


Pulsar discovery with 4-acre telescope



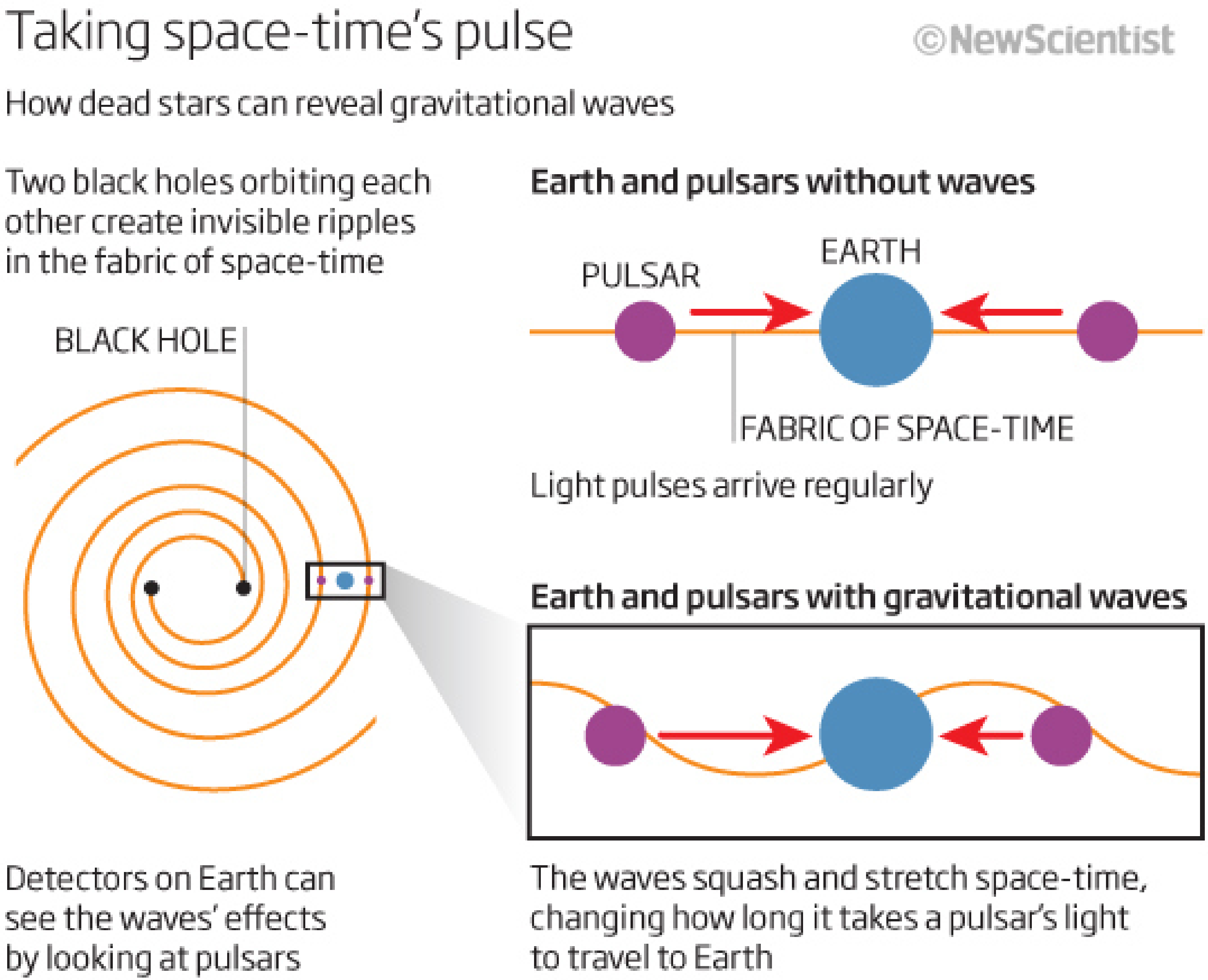
Jocelyn Bell Burnell, Anthony Hewish





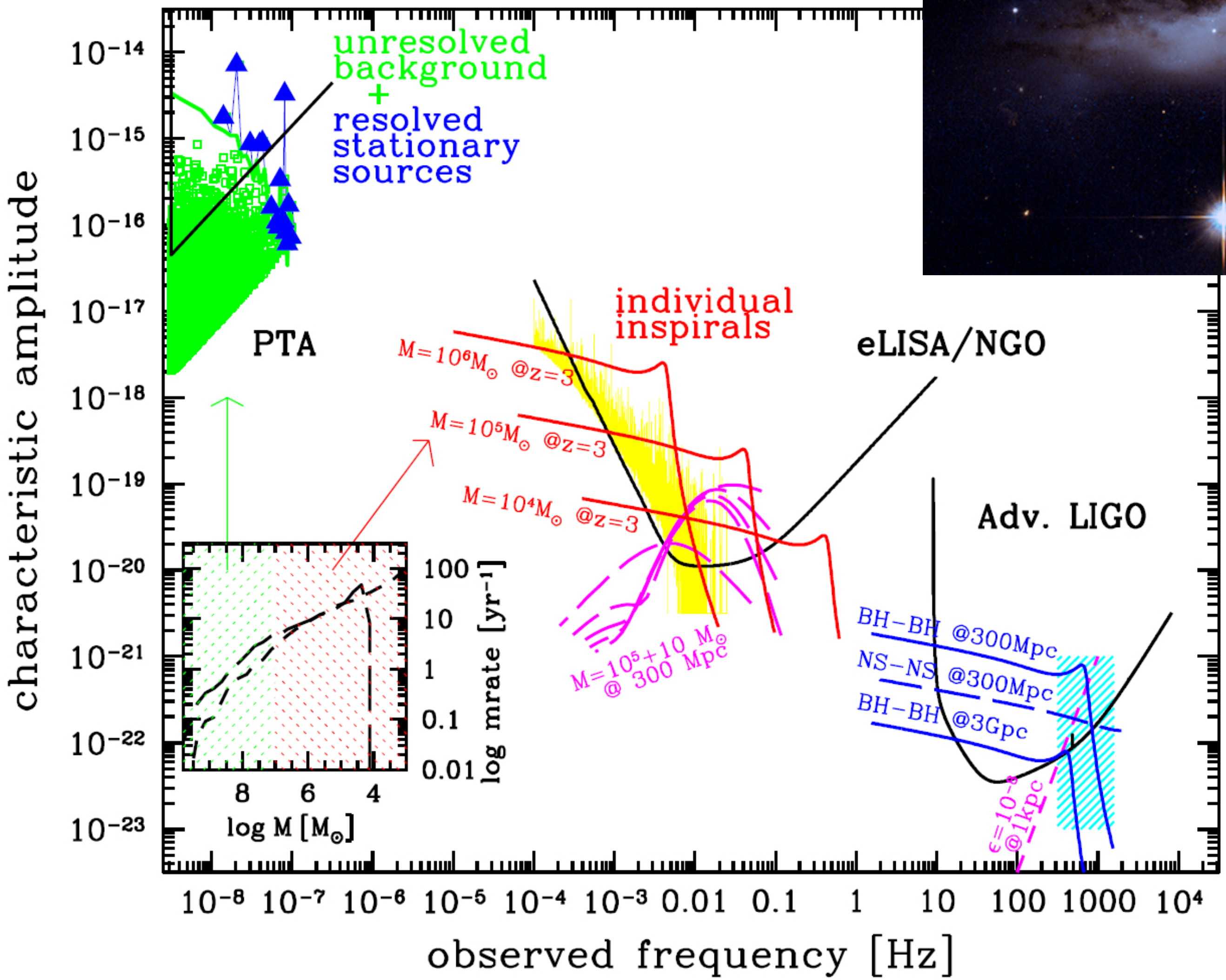
Hulse & Taylor
Binary Pulsar PSR1913+16

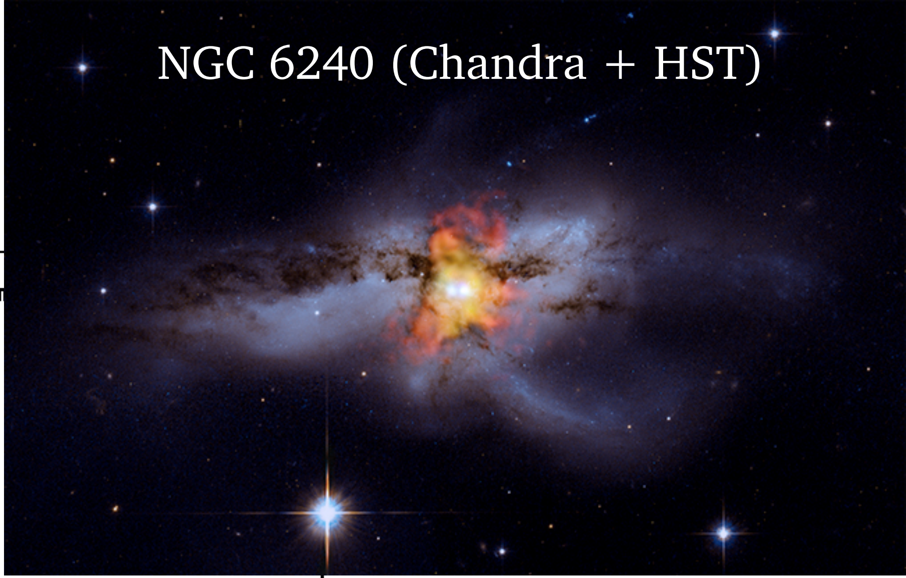
Gravitational waves from pulsar timing

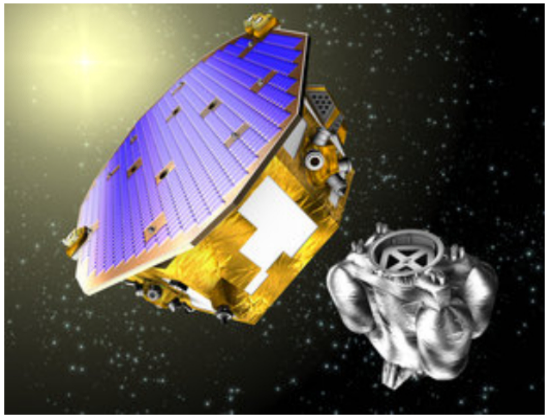


GW science Sesana arXiv:1304.0767

Gravitational wave science with laser interferometers and pulsar timing







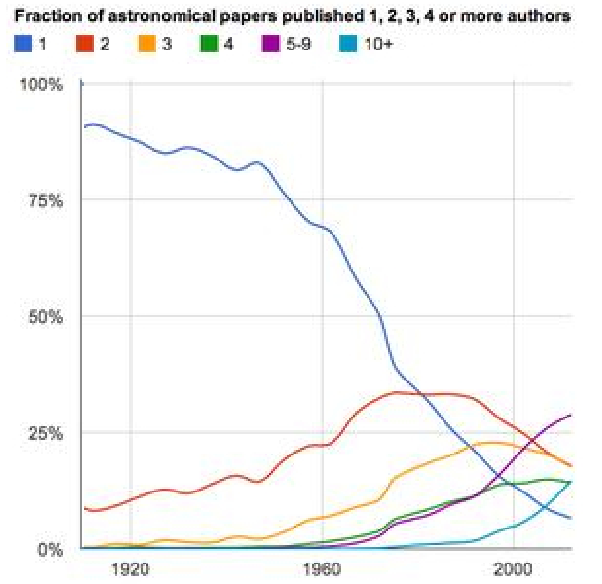
LISA Pathfinder is scheduled for launch in 2015.

Hanford, Washington

Livingston, Louisiana

Little Science, Big Science...and Beyond
by
Derek J. de Solla Price
Foreword
by
Robert K. Merton and Eugene Garfield

http://orbitingfrog.com/post/28714839175/authorship-in-astronomy



How to do good science (and get a job) in big science consortia? There is pressure to conform.

http://arxiv.org/abs/1008.1586 http://arxiv.org/abs/1207.3812
http://arxiv.org/abs/1108.5282 http://arxiv.org/abs/1305.5495

Too few theoretical astrophysicists are engaged in tasks that go beyond the refinement of details in a commonly accepted paradigm. It is far more straightforward today to work on these details than to review whether the paradigm itself is valid.

Avi Loeb

Society and astronomical discovery George Miley

- The creative nonconformist is more likely to be alienated by the world of accountability, work packages and deliverables that is essential for the development and construction of modern large astronomical instruments. This effect inevitably tends to reduce the fraction of nonconformists in modern 'big–science' astronomy.
- ... a "quota" of about 10% - 15% of creative difficult astronomers in each department and institute could substantially enhance the chances of future astronomical discoveries.

Science as a vocation Max Weber (1918)

- calculating external objects and mankind's activities
- methods of thinking, tools and training for thought
- to gain clarity [provided you are clear about things yourself]

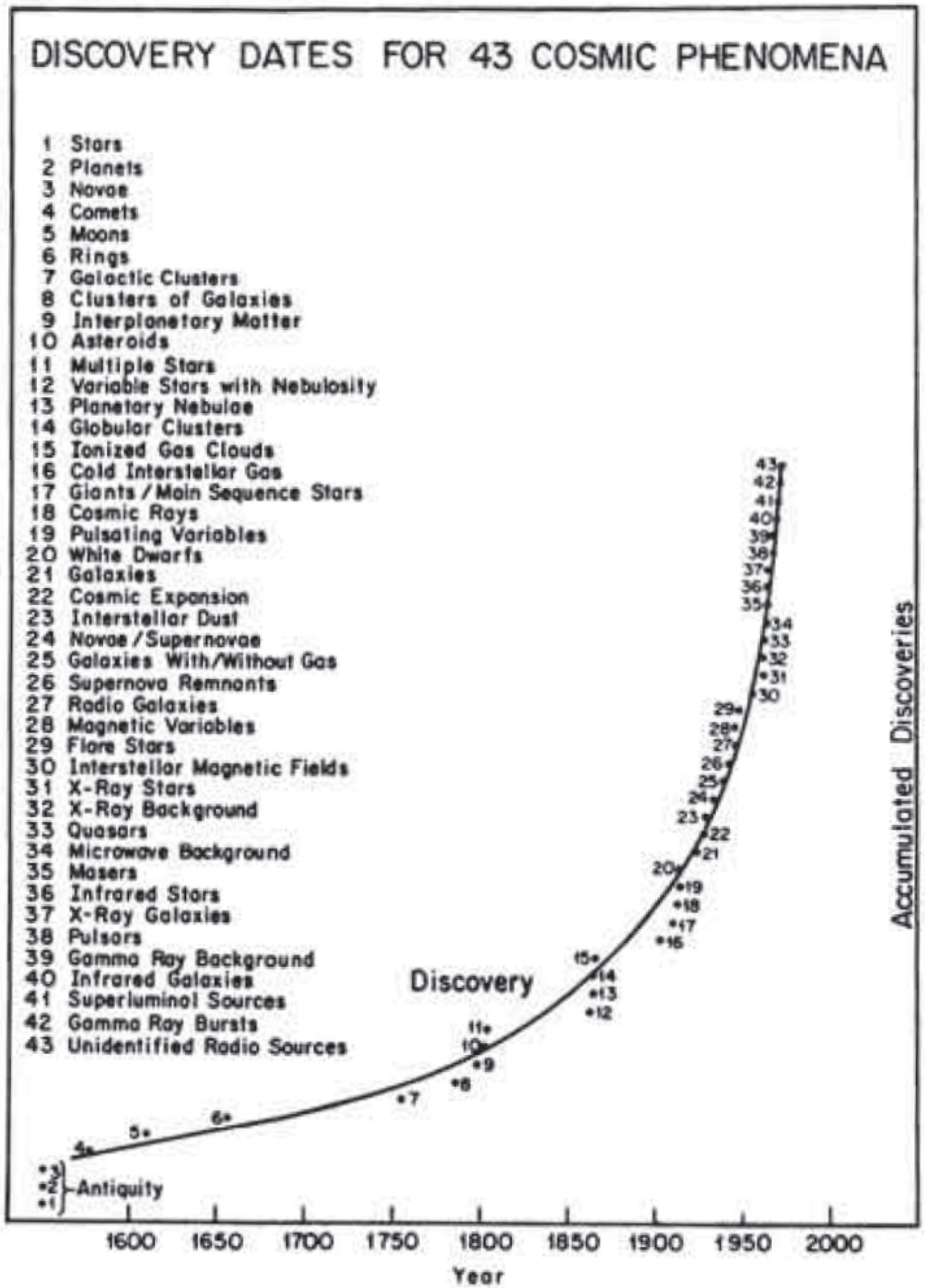
Science progresses as new knowledge is acquired

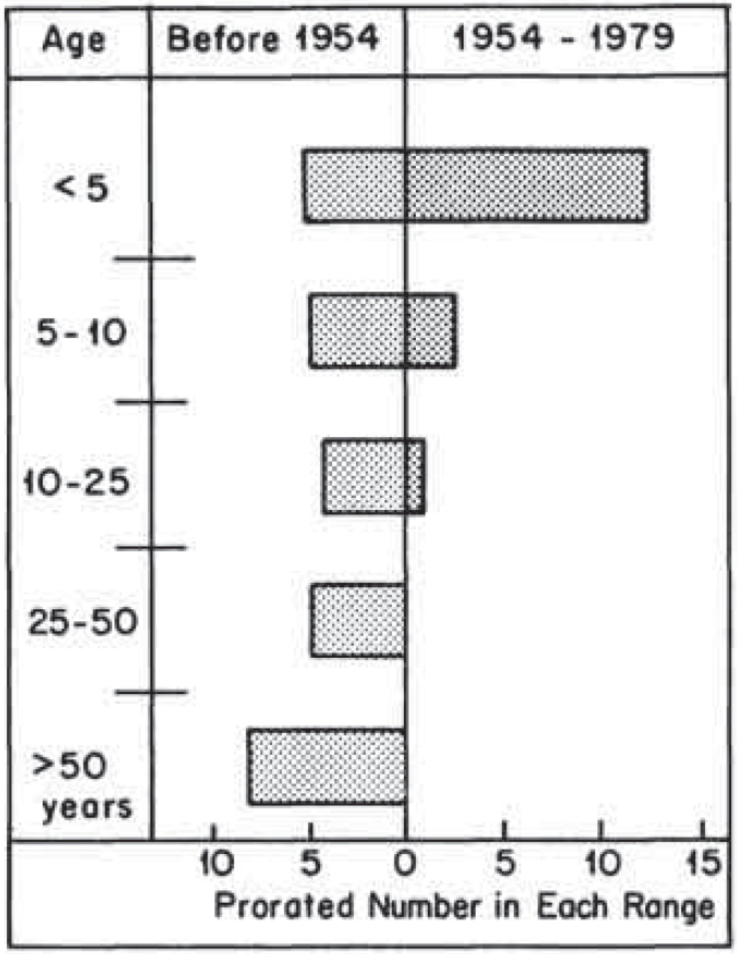
- theories should be falsifiable, i.e. subject to tests Popper
- most people work within a research programme
- programme can be abandoned: “paradigm shift” Kuhn

Science as a process to search for new ideas Selz

- reproductive thought in process to fill in a gap
- process of trial and error, with schematic anticipation
- creative new solutions if easy possibilities are exhausted

Popper's logic of research rests on Selz's cognition psychology





In recent times, discoveries are done soon after a new instrument became available

Harwitt 1981, 1983

All this curiosity driven science, is it of any use ?

Black hole explosions?

Hawking, Nature 248, 30, 1974

Rees, Nature 266, 333, 1977

A better way of searching for black-hole explosions?

Limits on cosmic radio bursts with microsecond time scales

O'Sullivan, Ekers & Shaver, Nature 276, 590, 1978

"there got to be a better way of doing this."

The invention came out of CSIRO's pioneering work in radioastronomy.

The US patent in question is no. 5,487,069, entitled 'Wireless LAN'.

U.S. Lawmaker Proposes New Criteria for Choosing NSF Grants

by Jeffrey Mervis on 28 April 2013, 3:48 PM | 260 Comments

drcrj • 4 days ago

I wonder what Rep Smith would have thought of the 1978 paper "Limits on Cosmic Radio Bursts with Microsecond Time Scales." Probably not much. But doing the astronomy behind this paper required creating new instruments, part of which is now incorporated into every WiFi device on Earth. Smith and his ilk have no concept of how science is done,

Computing challenges in all branches of astronomy

Millennium-XXL

Largest
high-resolution
N-body simulation

303 billion particles

L = 3 Gpc/h

~700 million halos
at z=0

~25 billion (sub)halos in mergers trees

$m_p = 6.1 \times 10^9 M_\odot/h$

12288 cores,
30 TB RAM on
Supercomputer JuRoPa
in Juelich

2.7 million CPU-hours

Angulo et al. (2011)

Trouble ahead in the Exaflop regime ?

10^{18} in 2018

How long would the Millennium-XXL take on a Exaflop Supercomputer at peak performance?
15 min

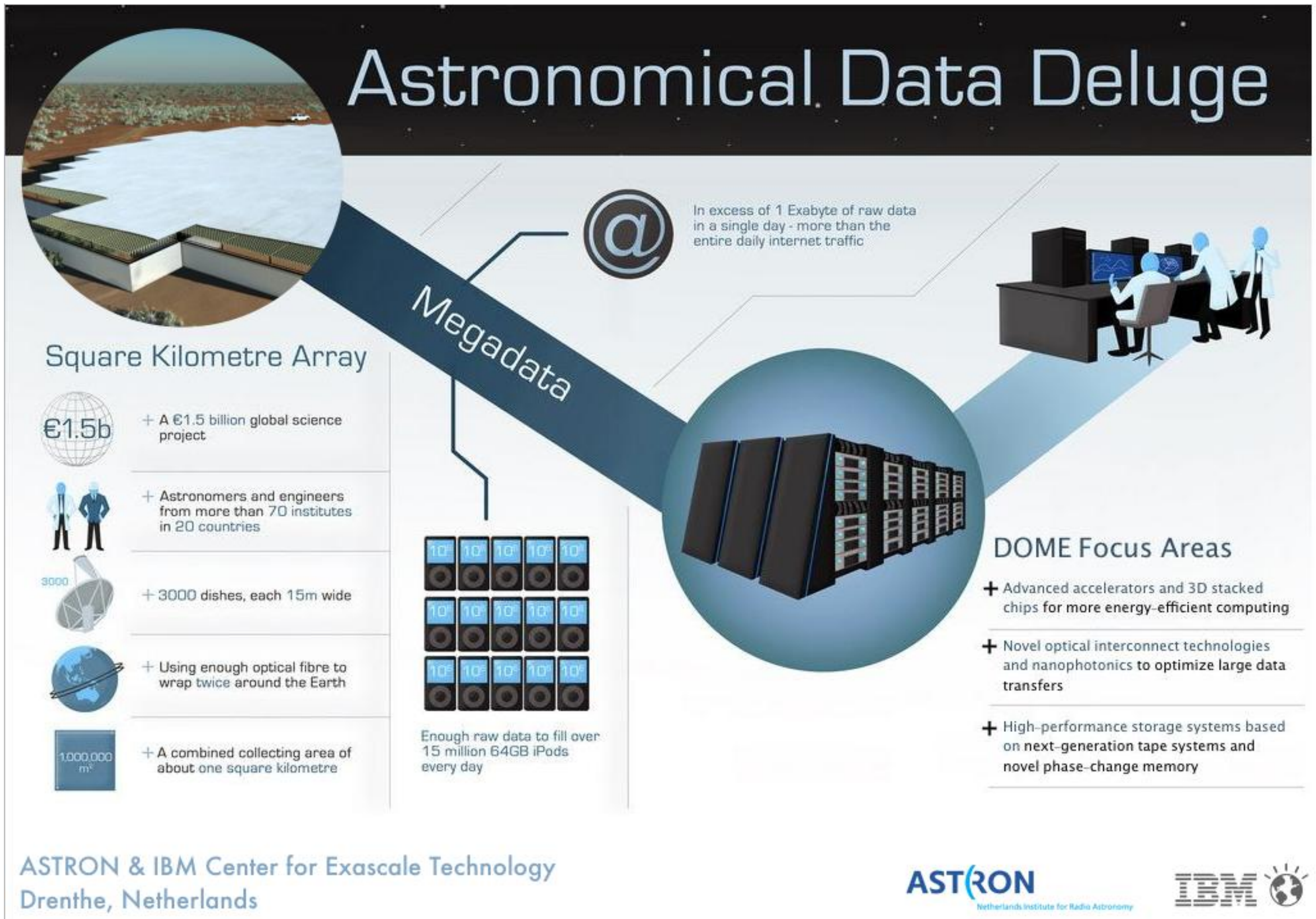
Figure by Volker Springel (Heidelberg)

One of the main problems:
Power Consumption

Petaflop Computer: **6 MW**

Exaflop Computer: **~ GW ?**

Need to get this down to **20-40 MW**



LOFAR

Besluit subsidies Investeringen Kennisinfrastructuur (Bsik)
Agentschap NL
Ministerie van Economische Zaken

SNN

water, energy, sensors

The IBM computer in Groningen is an integral part of LOFAR

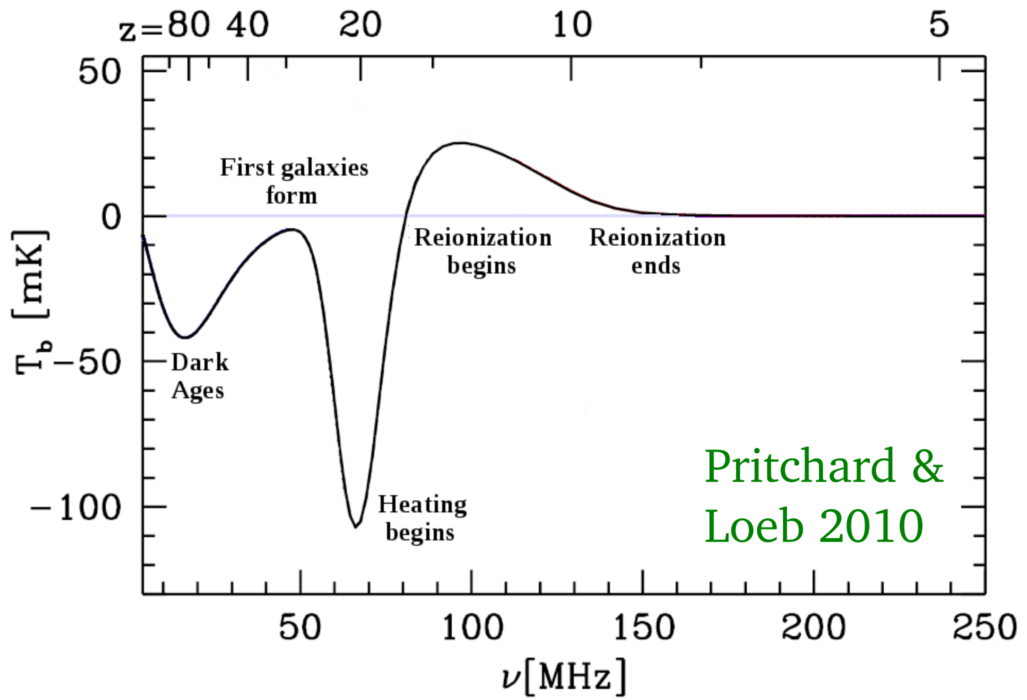
The key science projects of LOFAR are:

• Epoch of Reionisation	De Bruyn RUG+Astron
• Deep extragalactic surveys	Röttgering RUL
• Transient sources	Weijers UA, Fender, Stappers
• Ultra high energy cosmic rays	Falcke RUN
• Solar science and space weather	Mann AIP (D-Potsdam)
• Cosmic magnetism	Beck MpfR (D-Bonn)

Cosmic Dawn and the Epoch of Reonization

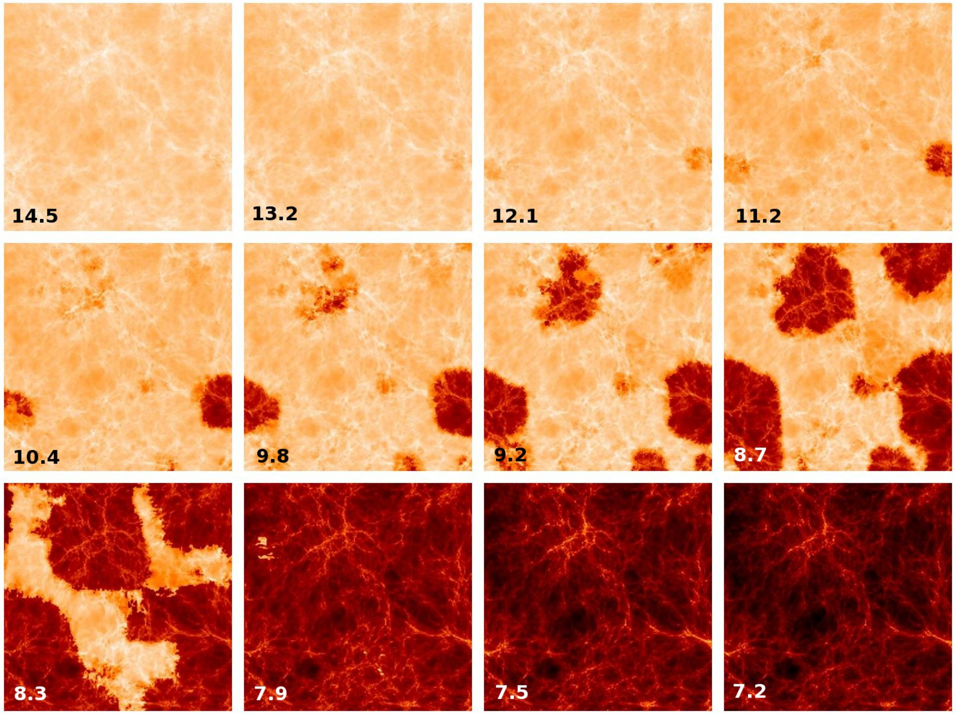
e.g. Lofar, MWA, PAPER

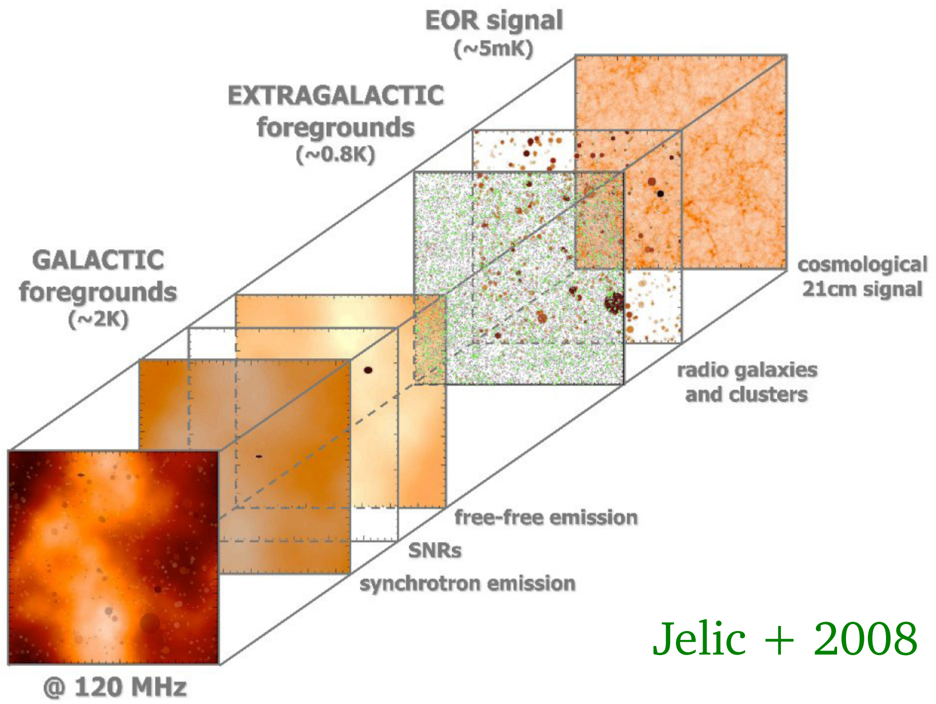
global 21-cm signal swamped by foreground



Pritchard & Loeb 2010

Furnaletto et al. 2004

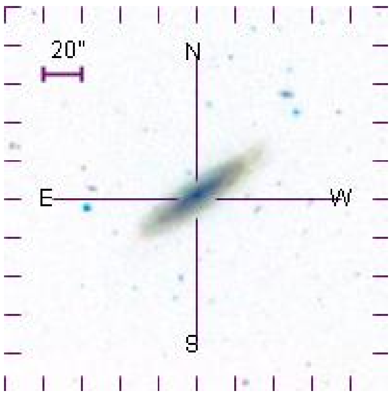


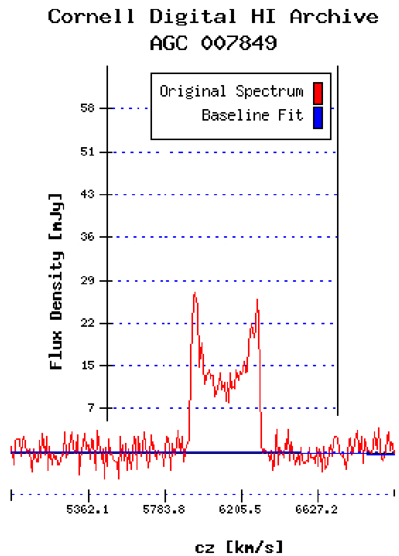


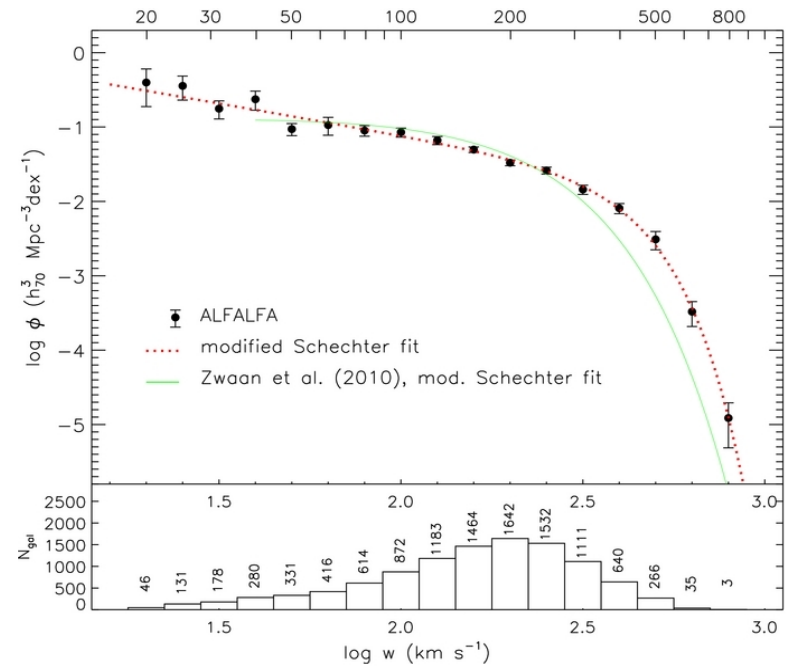
Jelic + 2008

HI velocity width function from ALFALFA

arxiv:1106.0710 Papastergis et al.







better than HIPASS at faint AND bright end

warm DM fits data better …

CF: don't confuse particle physicists

"Frontiers in Radio Astronomy and FAST"

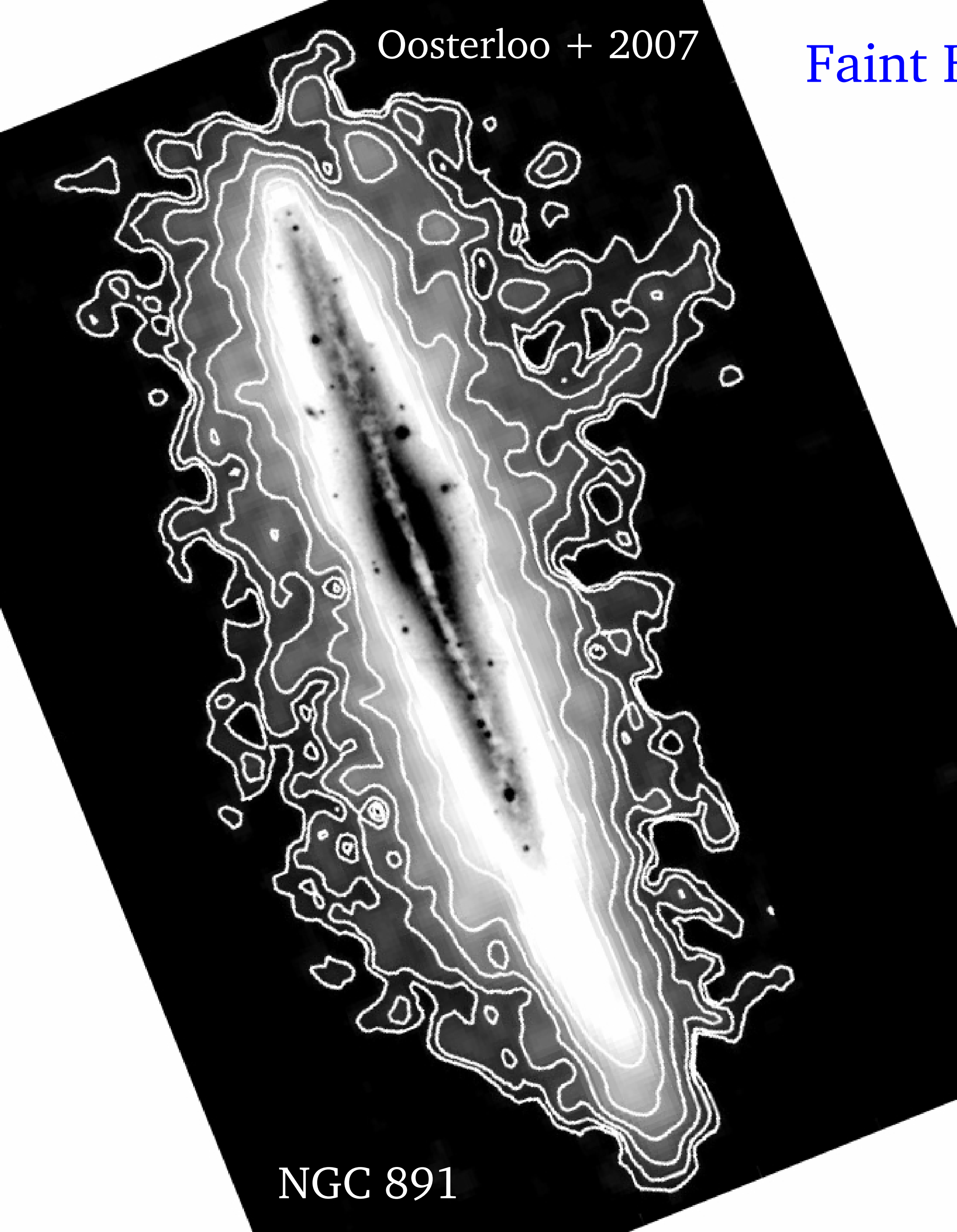
射电天文学前沿973 FAST radio973.bao.ac.cn

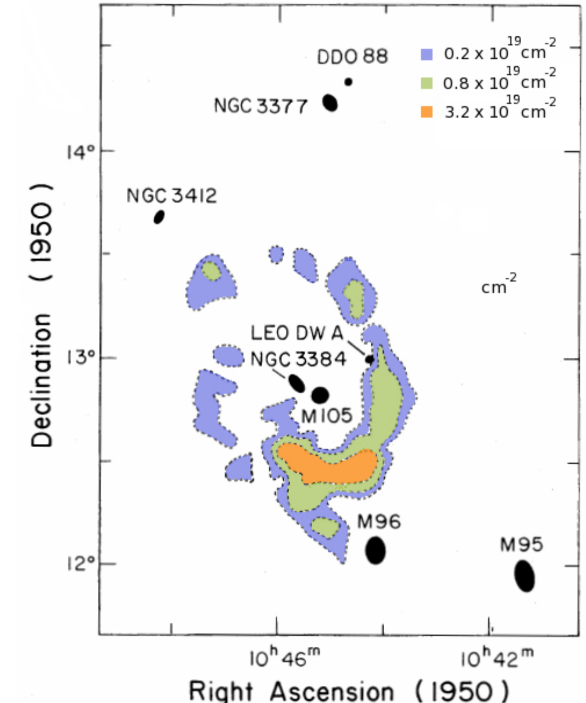
- 2011.3: Construction Start for FAST
- 2016.9: FAST first light
- 2020至2024: SKA phase I and phase II

Fundamental Science Proposal (973):2012～2016

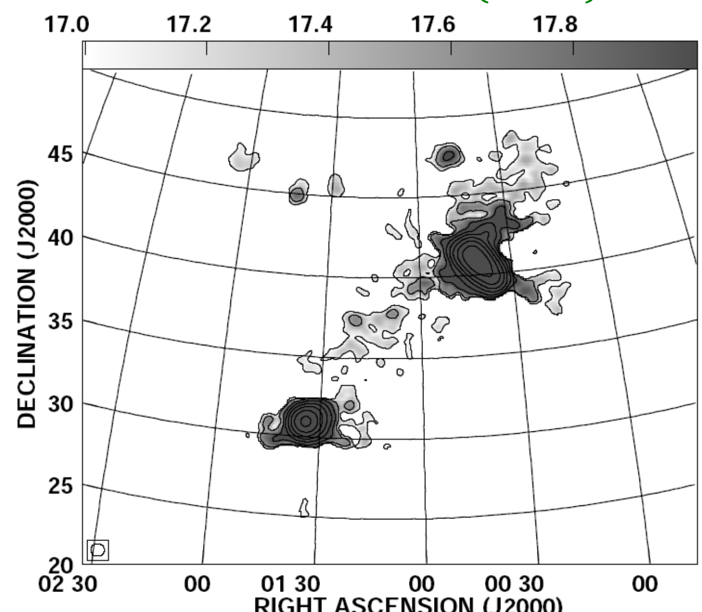
five science teams plus one receiver group, define key FAST programs and early science, train >30 graduate students and young radio astronomers

Faint HI





Schneider et al. (1989)

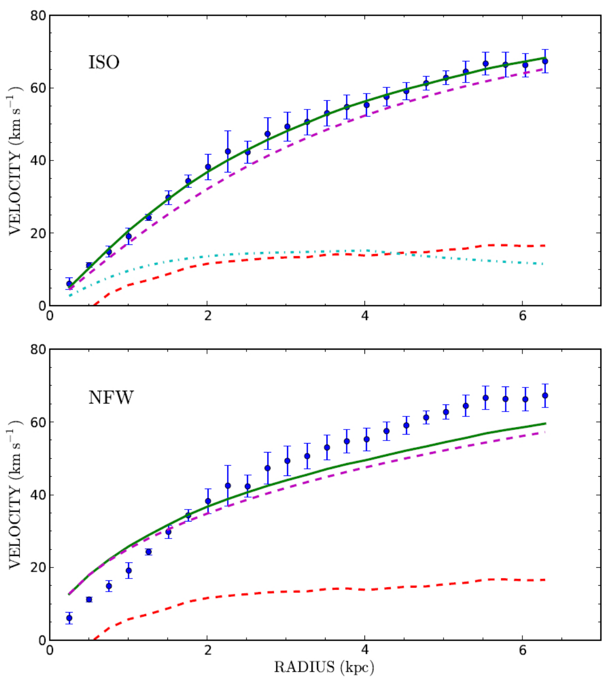


Braun & Thilker (2004)

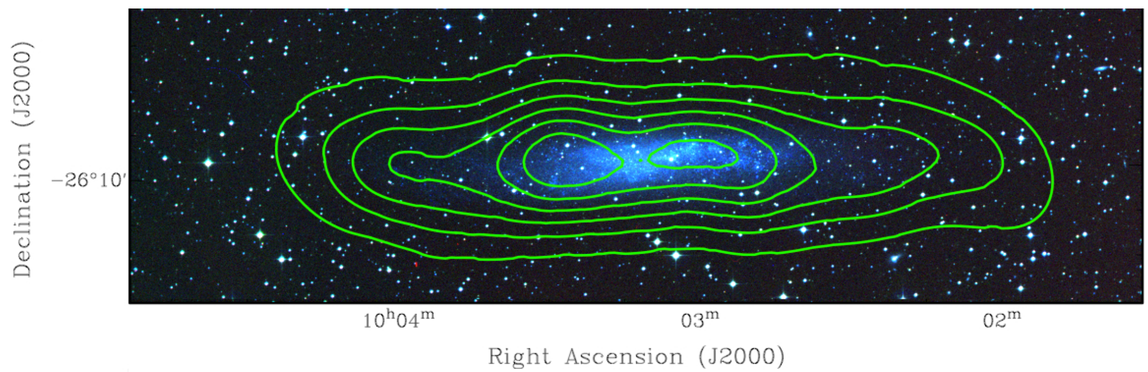
KAT-7/MeerKAT Commissioning

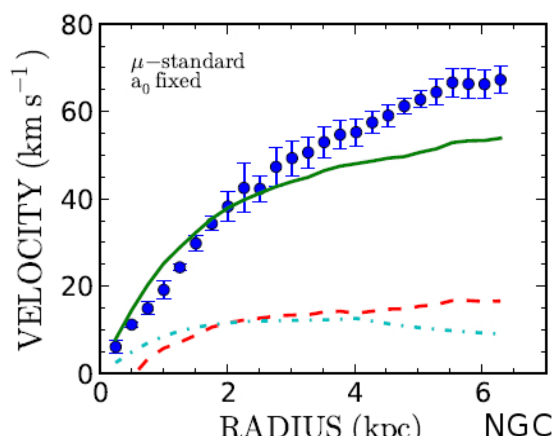
http://public.ska.ac.za/kat-7/kat-7-operations MeerKAT rollout

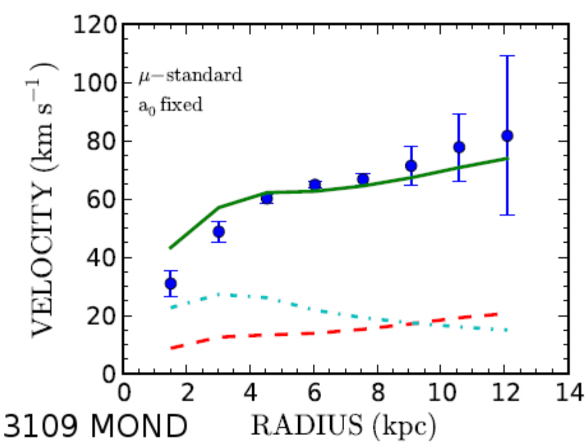
- 2014 - install test and commission 6 antennas
- 2015 - 29 antenna at about 3 per month
- 2016 - 29 in 8 months at about 4 per month
- Basic rule ... don't' panic, while we disprove ΛCDM and MOND



arXiv/1306.3227

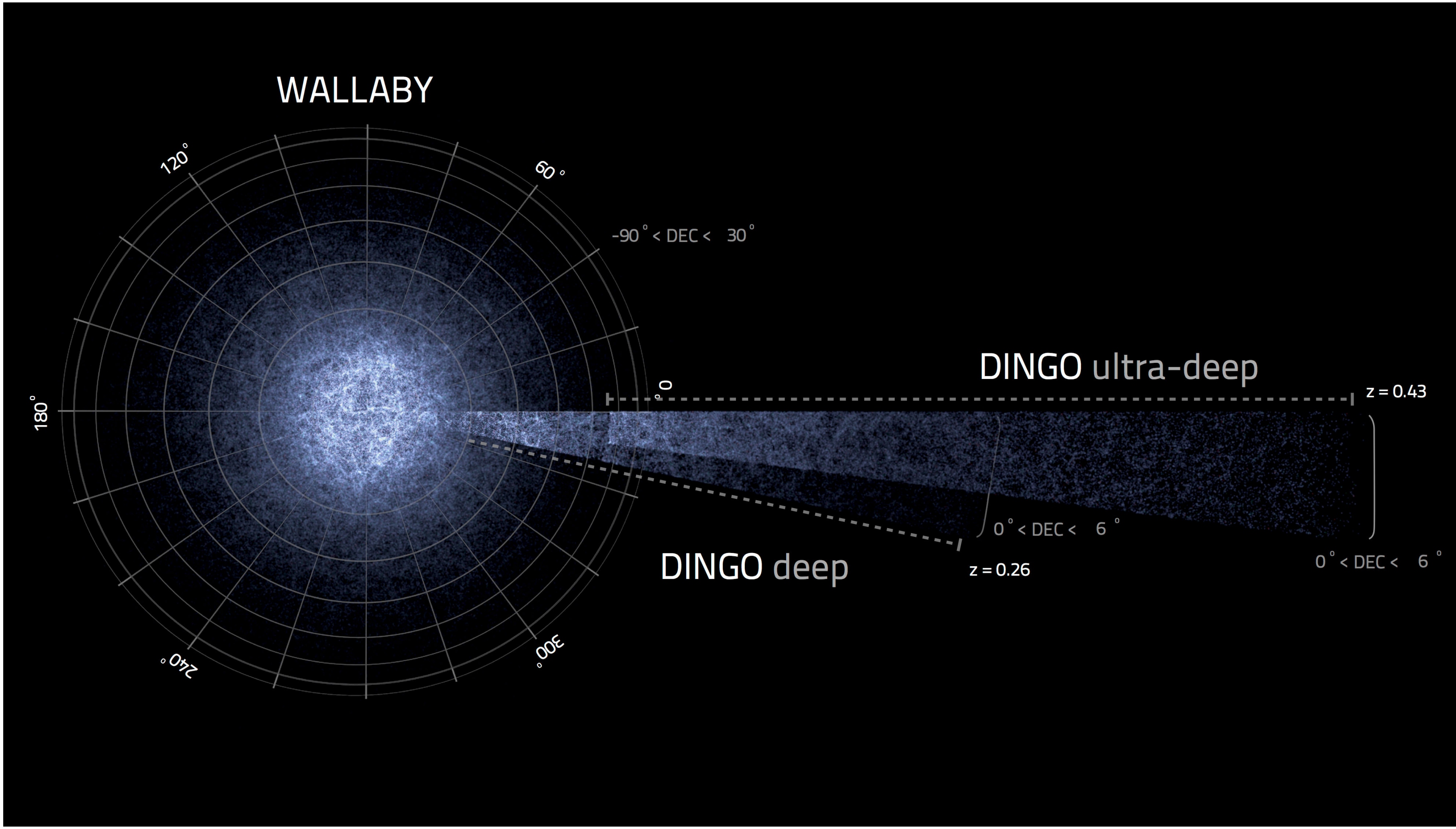






NGC 3109 MOND

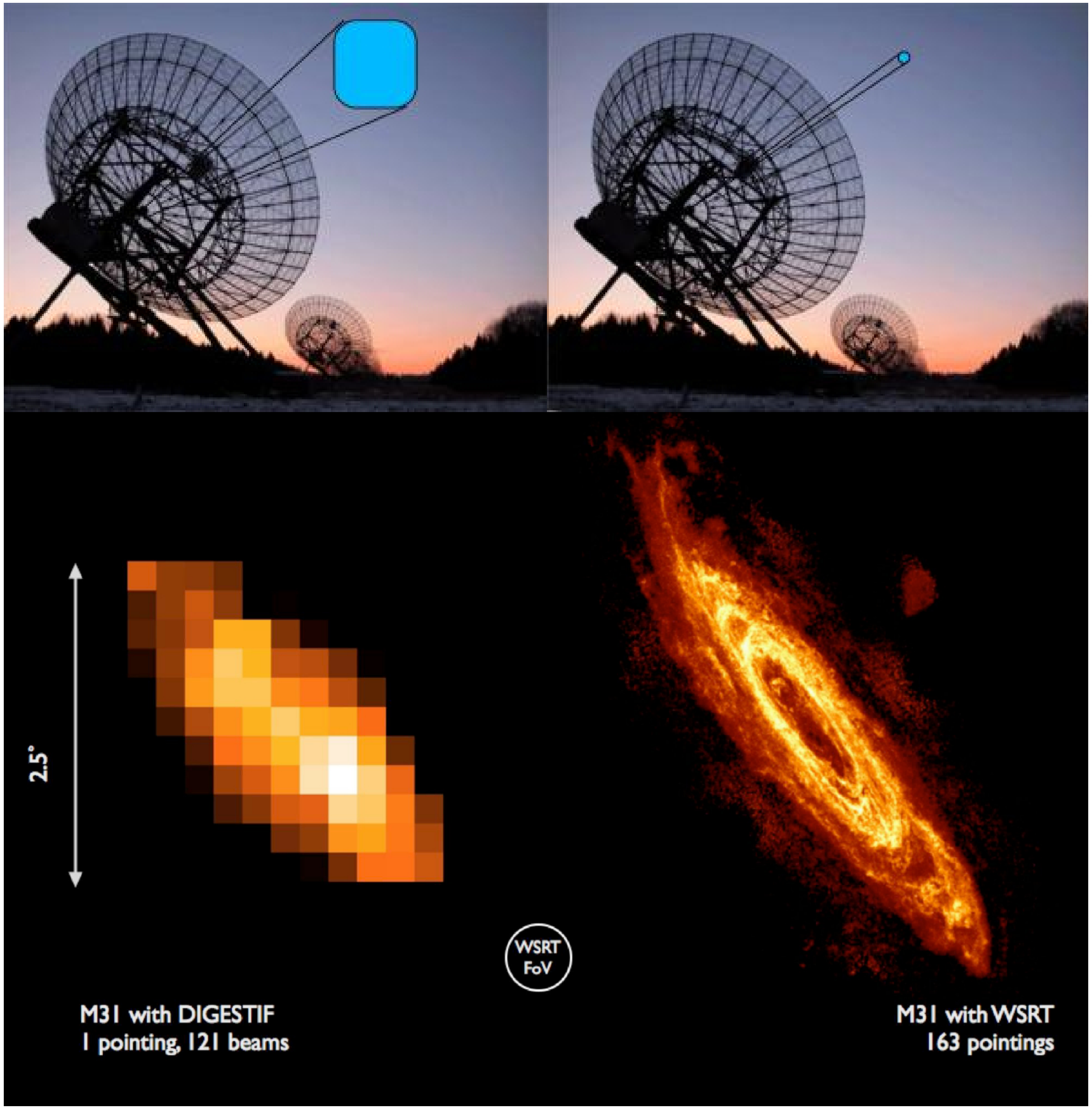
ASKAP HI surveys : shallow, deeper, deep Duffy et al. 2012



z = 0.26 : ~ 3 Gyr ago

z = 0.43: ~ 4.5 Gyr ago

Apertif development for the WSRT

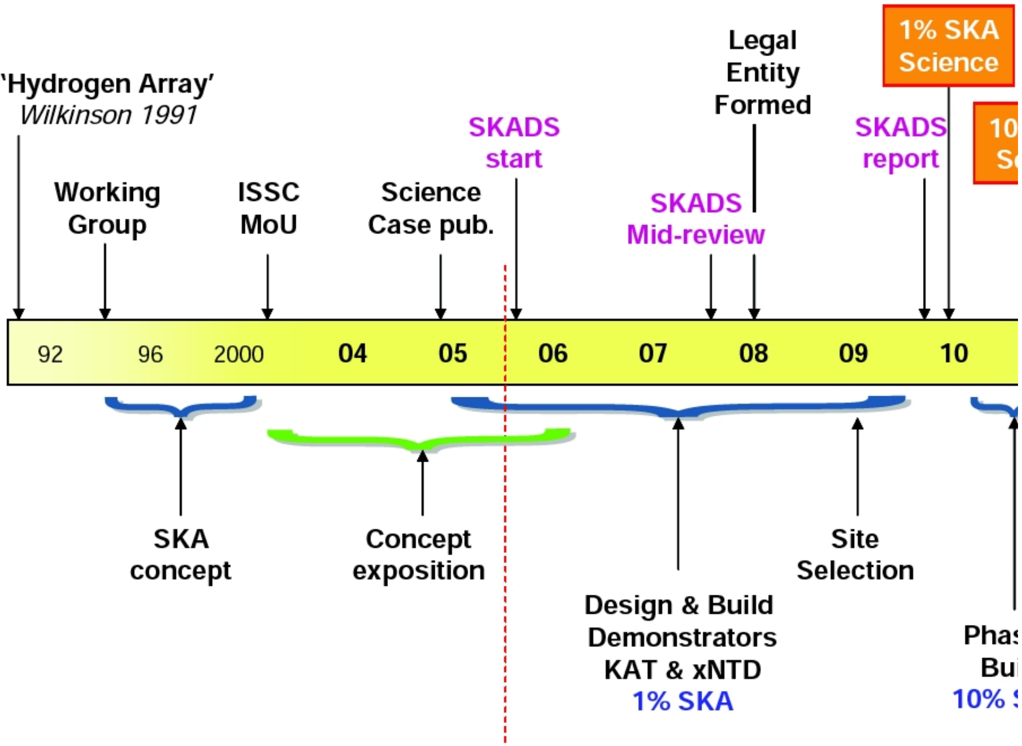


Phased Array Feeds increase the FOV

Oosterloo, Verheijen & Van Cappellen arXiv:1007.5141

When upgrade done, similar projects in HI as for ASKAP

SKA Timeline in 2005



TIMELINE at present

- **2024** — FULL OPERATION
- **2020–24** — PHASE TWO CONSTRUCTION
- **2020** — FULL SCIENCE OPERATIONS WITH PHASE ONE
- **2016–20** — PHASE ONE CONSTRUCTION
- **2013–15** — DETAILED DESIGN AND PRECONSTRUCTION PHASE
- **2012** — SITE SELECTION
- **2008–12** — TELESCOPE CONCEPTUAL DESIGN
- **1991** — SKA CONCEPT

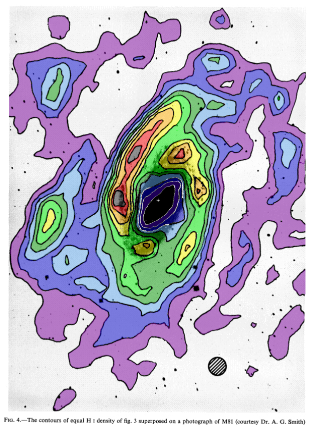
Timelines slip ...

The VLA was build on schedule, and within the budget [it took ∼ 10 years to get the computing to match the correlator hardware]

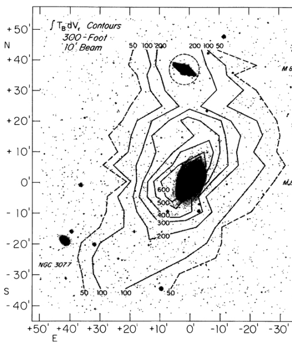
SKA will image galaxies such as M81 and N5055 at z ~ 1

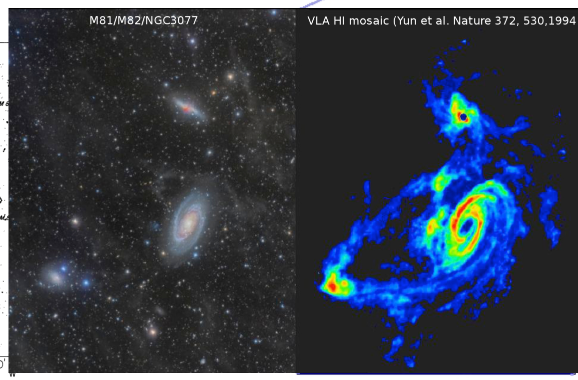
But at a small ratio Radius/Beamsize !

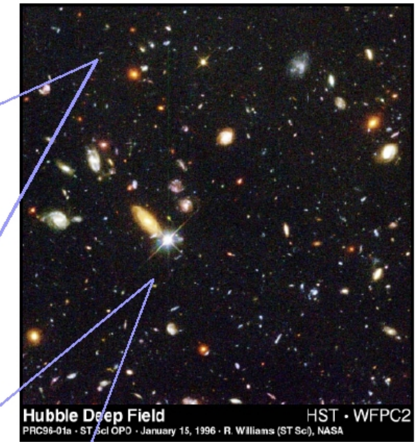
2.0 kpc

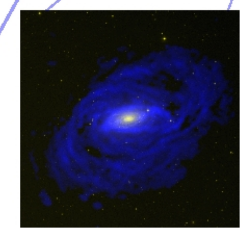


9.0 kpc









Van der Hulst et al. 2004

Detection limits for HI emission with SKA[a]

z	Frequency (MHz)	T_{sys}[b] (K)	Angular[c] resolution (arcsec)	Linear resolution (kpc)	SB dimming (mag)	Luminosity distance (Gpc)	Lookback time (Gyr)	HI mass[d] limit ($M_{\odot}$)
0.2	1183.67	50.4	0.52	1.7	0.796	0.972	2.41	6.1×10^{8}
0.5	946.94	51.4	0.65	4.0	1.486	2.825	5.02	8.7×10^{8}
1.0	710.20	53.8	0.87	7.0	3.026	6.640	7.73	2.7×10^{9}
1.5	568.16	57.5	1.09	9.3	4.000	11.02	9.32	7.2×10^{9}
2.0	473.47	62.7	1.31	11.1	4.796	15.75	10.32	1.5×10^{10}
2.5	405.83	69.6	1.52	12.5	5.469	20.72	11.00	2.6×10^{10}
3.0	355.10	78.3	1.74	13.6	6.052	25.87	11.48	4.3×10^{10}
3.5	315.64	89.3	1.96	14.6	6.566	31.15	11.83	6.7×10^{10}

[a] Assuming $t = 12$ h, $A_e/T_{sys} = 20000$, 2 polarizations and 70% of A_e within 100 km.
[b] Including a contribution from Galactic foreground emission assuming $T_{Gal}(f_{MHz}) = 20\left(\frac{408}{f_{MHz}}\right)^{2.7}$ K.
[c] Fixed array geometry assumed so that resolution scales with wavelength.
[d] Assuming 5 rms and 100 km s^{-1} profile width. At $z = 0.2$ and $z = 0.5$ the galaxies are assumed resolved so here the flux has been added over 8.5 and 1.5 beams respectively.

Full SKA : also probing the dark stuff (dark matter/dark energy)

Probing the dark ages

- Mapping out redshifted neutral hydrogen (H I) from the epoch of reionisation (EoR)

Galaxy Evolution, Cosmology and Dark Energy

- Dark energy via baryonic oscillations traced by the 3-d galaxy distribution in the Universe
- Galaxy evolution as a function of cosmic time (H I observations in emission and absorption)

Strong Field Tests of Gravity

- Tests of theories of gravity via binary pulsars with neutron star and black hole companions
- Detection of nano-Hertz gravitational radiation using pulsar timing arrays

Fundamentalist physics: why Dark Energy is bad for Astronomy

Simon D.M. White

arXiv:0704.2291

Max Planck Institute for Astrophysics, Garching bei München, Germany

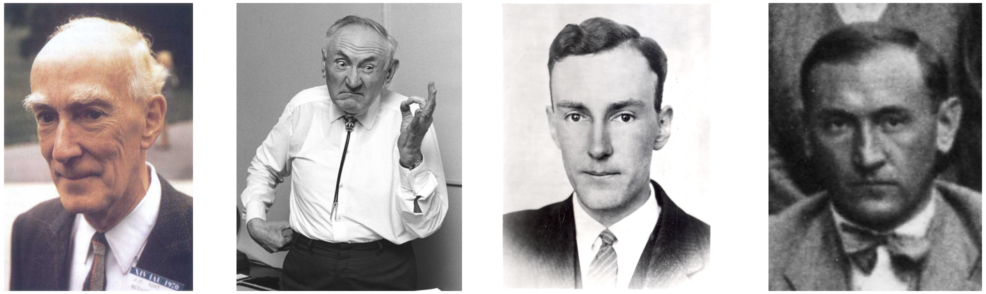
Astronomers carry out observations to explore the diverse processes and objects which populate our Universe. High-energy physicists carry out experiments to approach the Fundamental Theory underlying space, time and matter. Dark Energy is a unique link between them, reflecting deep aspects of the Fundamental Theory, yet apparently accessible *only* through astronomical observation.

New instruments bring fresh opportunities for discovery

SKA/pre-SKA : EoR with 21-cm line detection
GW background with pulsar timing arrays

Big science is now the new reality (think e.g. LHC – Higgs)

This can lead to more emphasis on 'the big picture' and on 'transformational' science, opposed to 'incremental' science



Oort : Looking ahead in wonder

Zwicky : Wonder is the origin of all great achievements
Without it, life is drab, and thought is sterile