(Some) slides taken from other talks by Eduardo Ros, Michael Kramer, Lourdes Verdes, Leonardo Testi, John Monnier, and VLTI, SKA and ALMA web pages.
At radio wavelengths, the resolution is limited by diffraction.

At optical wavelengths, the resolution is limited by the atmospheric fluctuations.
Resolution / Difraction

Resolution = \frac{\lambda}{D}

- \lambda = 10 \text{ cm} \quad \text{R}=70'' \quad \text{(Arecibo)}
- \lambda = 550\text{nm} \quad \text{R}=1'' \quad \text{(my telescope)}
- D = 300 \text{ m}
- D = 0.2 \text{ cm}
Historic note: the need for interferometry

Grote Reber antenna and fist map of the sky (900 Mhz) ca. 1940
Better resolution: 
increasing D: the size matters (?)
INTERFEROMETRY

Young's Double Slit Experiment

Coherent Light
Laser Light

Light Propagation Direction

Destructive interference
Barrier with Double Slits

Constructive interference

Figure 4 Intensity Distribution of Fringes

Intensity

sin θ

-2λ/d -λ/d λ/d 2λ/d
VLA (Very Large Array): 27 antennas, 25m diameter

This array may reach an angular resolution equivalent to a single telescope as large as 36km.

Images: NRAO (Socorro)
Interferometry at work

- Having a telescope, is it possible to get a (good) image even if we mask the primary, except for some holes?
- Image quality as a function of the hole number?

Let’s do it...
Interferometry at work

Nº of holes for each step:
2, 4, 8, 16, 32, 64, 128, 256, 512, 1024
We can combine telescopes in different places around the Earth (and space).

**VLBI**

Resolution is routinely 100 times better than that of the HST (0.1 milliarcsecond)
Very Long Baseline Interferometry (VLBI)

- Need of atomic clocks for precise time signals.
- The signal is combined down to video (0-2 MHz)
- Video tapes / disks are correlator days or weeks later, but...
- ... e-VLBI !!
Science with new interferometers

ALMA, SKA, VLTI

“Prediction is very difficult, especially about the future”.
– Niels Bohr
Atacama Large Millimeter Array

- At least 50 x 12m Antennas
- Frequency range 30-1000 GHz (0.3-10mm)
- 16km max baseline (<10mas)
- ALMA Compact Array (4 x 12m and 12 x 7m)

1. Detect and map CO and [C II] in a Milky Way galaxy at z=3 in less than 24 hours of observation
2. Map dust emission and gas kinematics in protoplanetary disks
3. Provide high fidelity imaging in the (sub)millimeter at 0.1 arcsec resolution
ALMA observes a ring around the bright star Fomalhaut

This view shows a new picture of the dust ring around the bright star Fomalhaut from the Atacama Large Millimeter/submillimeter Array (ALMA). The underlying blue picture shows an earlier picture obtained by the NASA/ESA Hubble Space Telescope. The new ALMA image has given astronomers a major breakthrough in understanding a nearby planetary system and provided valuable clues about how such systems form and evolve. Note that ALMA has so far only observed a part of the ring.

Credit:
Quick Overview of SKA

- 1000 -1500 antennas x15m in 5km
- 1000 -1500 antennas x15m up to 3000 km

70 MHz - ≥ 25 GHz
4-3m - 1.2 cm

200 - 1 SQ^2 FOV
0.1” - 0.001” resolution

Interferometers can be incrementally built

- **SKA1** = 10% collecting area, 70 Mhz - 3 GHz, ~350 M€, 2016 - 2019
- **SKA2** = 100% collecting area, 70MHz - 10 GHz, ~1100 M€, 2018 - 2023
- **SKA3** High frequencies: ≥ 25 GHz. No defined dates
- $2 billion total cost
Antennas

Frequency range > two decades:
Combination of different types of antennas

Can observe towards several directions simultaneously

Aperture Array
70 - 450 MHz
Baselines 100 km

SKA1 2016 - 2019

single pixel feed
450 MHz - 3GHz
baselines 100 km
Advanced Instrumentation Program = AIP

Enhancing FOV

dense aperture array

200 - 500 MHz

200 deg²

SKA2

2018 - 2023
Square Kilometre Array Board has decided joint operation between Australia, South Africa.
1. SKA is a survey instrument. ALMA is more adequate to detailed follow-up (limited FoV).

2. Complementary frequency range:
   SKA: 0.1 – 25 GHz
   ALMA: 30-950

3. Similar resolution:
   SKA: 1 mas (25GHz, 3000km baseline)
   ALMA: 5mas (950GHz)

4. Both are sensitive different emission processes.
   ALMA (in essence) : elements heavier than H
   SKA (in essence too): HI -- 21cm

5. Both far in the South...
SKA Key Science Drivers

1. Probing the Dark Ages
   - When & how were the first stars formed?

2. Galaxy Evolution, Cosmology and Dark Energy
   - Nature of Dark Energy and Dark Matter

3. Strong-field tests of General Relativity
   - Was Einstein correct?

4. Origin & Evolution of Cosmic Magnetism
   - Where does magnetism come from?

5. Cradle of Life
   - What and where are the conditions for life?
1- Probing the Dark Ages

The Dark Ages
Era of the Universe from 300 000 - 1 000 000 000 yr after the Big Bang during which the first stars and galaxies formed
- Probing the Dark Ages

SKA Role (< 200MHz)
Detect and image HI in the dark ages - shed light on the physics of the formation of the first objects in the Universe

Furlametto et al. 2004

COSMIC HISTORY OF THE UNIVERSE
1- Probing the Dark Ages

SKA Role (< 200MHz)
Detect and image hydrogen in the dark ages - shed light on the physics of the formation of the first objects in the Universe

ALMA
ALMA (with compact array) will be extremely sensitive to arcmin-scale CMB power, from clusters, filaments and primordial fluctuations
1- Probing the Dark Ages (first metals)

SKA Role (operating > 25 GHz)

• Complementary information of the very first galaxies (z > 5)
• Lower order emission lines from CO, HCN

ALMA

• ALMA will see higher CO transitions for z > 5 (but not the three lowest)
1- Probing the Dark Ages (first metals)
2- Galaxy Evolution, Cosmology and Dark Energy

• Galaxy assembly, steadily, from smaller to larger systems.
• Star formation seems to reach a peak at $z \sim 2$

Relation between these two processes?

• SKA role:
  - measurement of HI (basic ingredient)
  - estimate of star formation rate

• ALMA:
  - measurement of the mass of molecular gas; CO trans.
  - powerful tracer of star forming galaxies out to $z \sim 3$ (and starbusts to $z \sim 10$)
3- Strong-field tests of General Relativity

**SKA role**

Identify and time pulsars with nano-second accuracy

- **Gravity**
  - Test GR around Black Holes

- **Clocks**
  - Sensitive gravity wave detector

**Surpass all proposed tests**

**SKA will find 20,000 pulsars in our Galaxy**

**Complementary to Adv. LIGO/LISA**
SKA will observe pulsar - black hole binaries, allowing precise tests of strong-field general relativity and measurement of black hole spin.

ALMA (as the key element of a sensitive mm-VLBI array) will image the event horizon around the nearest supermassive black holes (Sgr A* and M87). Measurement of the black hole spin.
Magnetic fields are crucial in:
- galaxy & star formation
- turbulence & gas motions
- acceleration & propagation of cosmic rays
- Evolution and structure across cosmic time.

Radio observations provide a unique probe of cosmic magnetic field
- Synchrotron emission, Polarization
4- The Origin and Evolution of Cosmic Magnetism

SKA role:
- All sky survey of Faraday rotation measures (RM) of 100 000 background sources
- “RM grid” for probing magnetism in the Milky Way, nearby/distant galaxies, clusters, protogalaxies...
- Map out evolution of magnetism for $z > 5$ to present

ALMA role:
- ALMA will have the capability of observing continuum polarization.
- Some starburst galaxies will be bright enough to be detected at $z > 5$ (Wielebinsky 2006)
- Identify targets for further very deep SKA observations.
SKA Role

Movies of proto-planetary disks in formation

Composition of 'building blocks' of disks

Probe the 'Habitable zone' in disks

Complements ALMA

Complementary to ALMA/ELT

Theoretical Simulation
Protoplanetary disks with ALMA

Birth of planets
- $M_{\text{planets}} / M_{\text{star}} = 1.0 M_{\text{Jup}} / .5 M_{\text{star}}$
- Orbital radius: 5 AU at 50 pc distance
- Disk mass = circumstellar disk around the Butterfly Star in Taurus

ALMA 850 GHz
Protoplanetary disks ALMA / SKA

- Both arrays can resolve protoplanetary disks around the nearest stars
- Expect to detect gaps caused by Jupiter-mass planets
- May also be able to see heated dust associated with forming giant planets
- Which frequency to use depends on the distribution of grain sizes: we know that debris discs radiate at 1mm; we also know that HL Tau b is clearly visible at 1cm.
Astrobiology / prebiotic molecules

**SKA:**
- These (or other) molecules have been already detected by their low-energy transitions (longer wavelengths).
- Example: glycolaldehyde (CH$_2$OHCHO), detected by the GBT from observations of transitions frequencies from 13 to 22 GHz.

**ALMA:**
- Prime instrument to probe of molecules in interstellar clouds (high spatial resolution, short-wavelengths).
SKA dedicated time to SETI-like projects, but…
... no, it won't work like this...
VLTI
Very Large Telescope Interferometry
VLTI
Very Large Telescope Interferometry
AMBER/VLTI OBSERVATIONS

RS CAP

- MR-K (2.13 - 2.47 µm, R~1500).

- Resolution ~8 mas

- Continuum emission + $^{12}$CO (2-0), (3-1), (4-2) + $^{13}$CO (2-0).
AMBER/VLTI OBSERVATIONS

RS CAP
AMBER/VLTI OBSERVATIONS

**RS CAP**

CO opacity change the size ~10-15%

Systematic increase for $\lambda > 2.3 \, \mu m$ (!!)
Stellar structure models (MARCS) are not able to account for the CO features observed: either M (mass) is not well estimated and/or the emission region is very extended (~3 R or more).

-Evidence of water vapor in a extensive region of the atmosphere of RSCap.

-Other AGBs being analyzed.
We observed ABDorA in P86
AMBER instrument LR-JHK
A0-K0-G1 (largest resolution in P86)

Time allocated: 10 hr, 25 December 2009
VISITOR mode
VLTI/SINFONI - Thatte et al. 2007; Close et al. 2007
How (NIR) interferometry can help?

• Age of the system: 25 to 120 Myr

• The size of ABDorA can provide bounds to the age of the system, as it contracts towards the main sequence (provided A and C are coeval).

• Example: AMBER/VLTI, K-band, AT’s with largest baselines
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PMS stars get less resolved as they contract (smaller size)
Size of ABDorA

ABDorA
UD-diameter = 0.62±0.04 mas

Limb-darkening correction:
LD-diameter = 0.60±0.04 mas

Distance: 14.9 ± 0.1 pc
(Hipparcos +VLBI series)

R = 0.96±0.06 R☉
Comparison of measurements (M and R) with PMS models in the M-R plane

ABDorC age range 40-120 Myr
Magnetic field in ABDor

- Strong magnetic field (≈200G)
- Fast rotator (12hr)
- Frequency and durations of sunspots

Strong magnetic activity

- There are previous evidences of a connection between magnetic activity and stellar size (Ribas et al. 2003; Torres et al. 2006).
- Loss of efficiency in convection, that leads to

Larger radius
(10-15% than that expected in absence of magnetic activity)
New observations scheduled for Dec 27th 2012