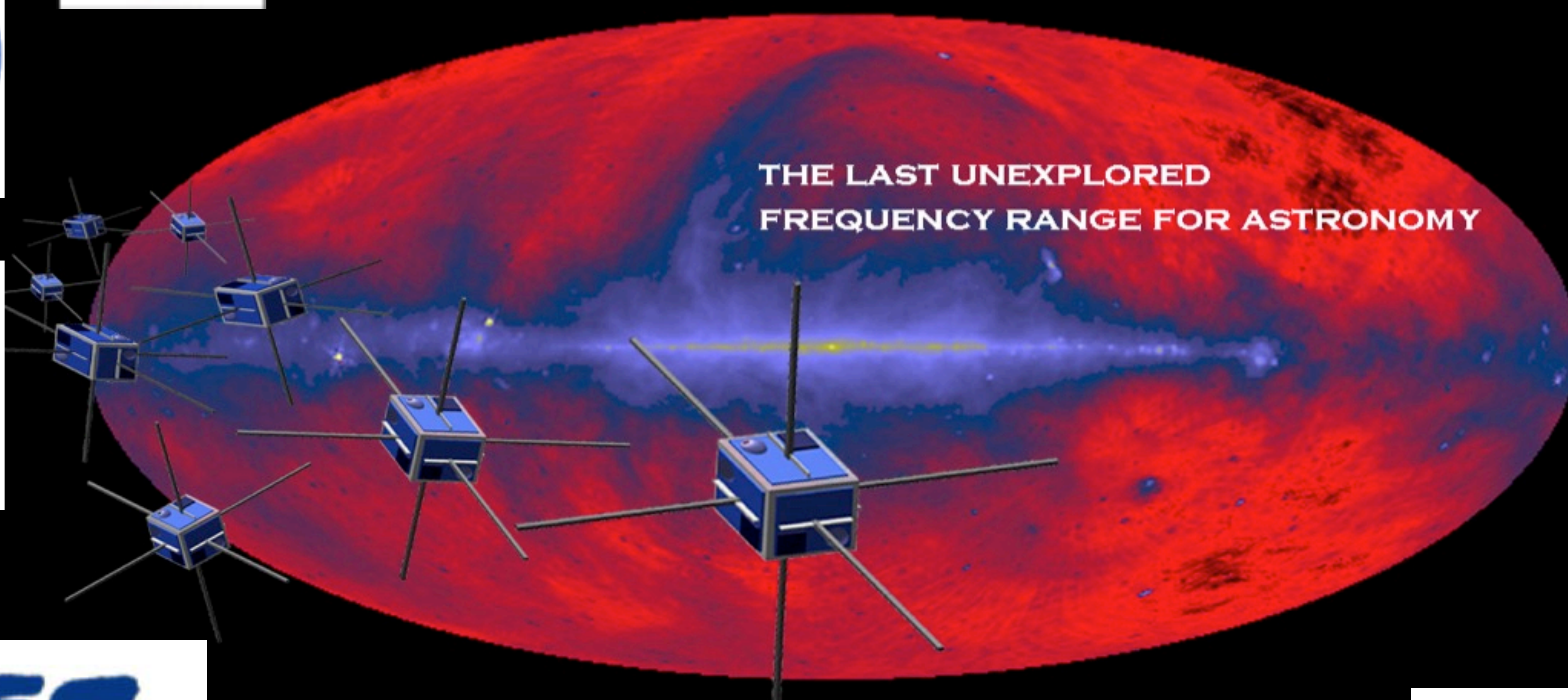
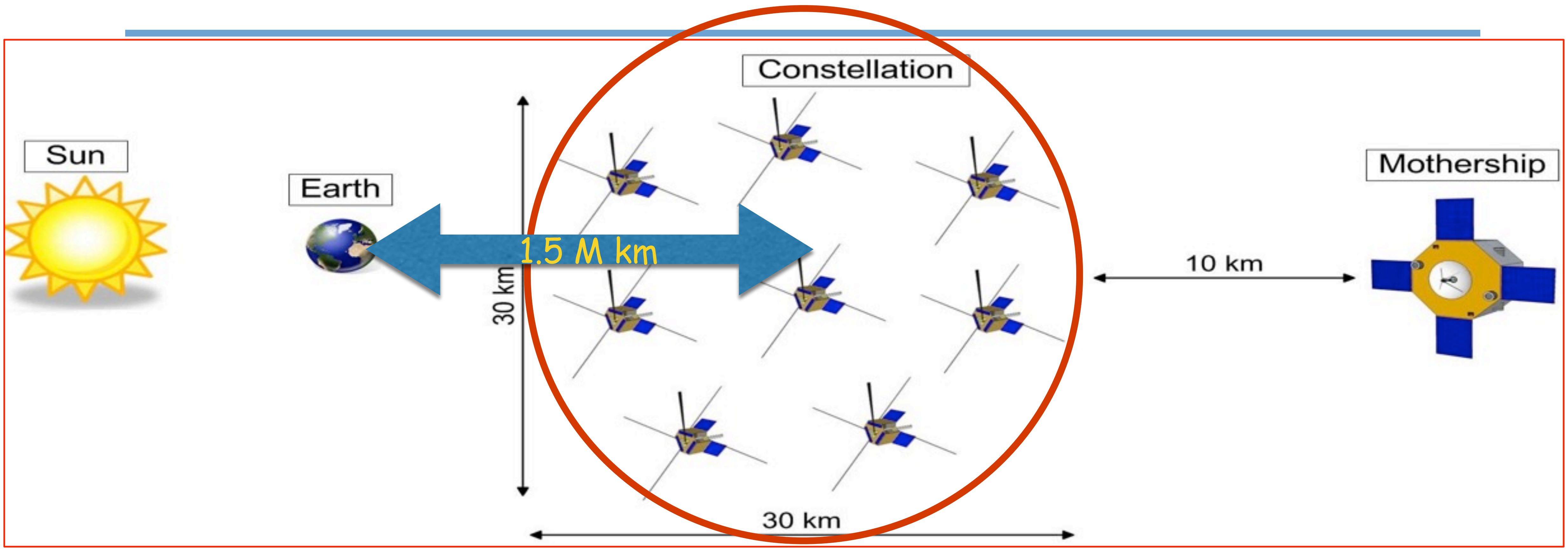
Discovering the Sky at the Longest Wavelengths — Space-Based Ultimate-Low Frequency Radio Observatory at Sun-Earth L2

Tao An - SHAO, CAS
Albert-Jan Boonstra - ASTRON
et al.

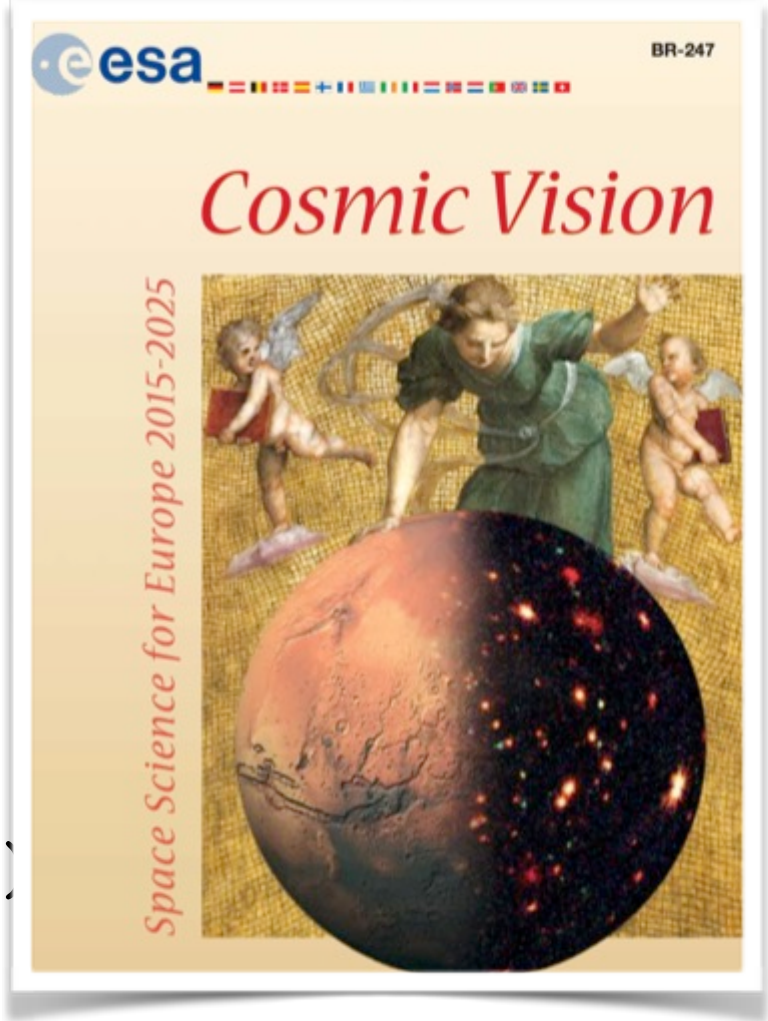


Mission Concept



- A high-sensitivity high-resolution space-based aperture array working at frequency range 1-80MHz
- A constellation: A mother + 12 slowly drifting Children => interferometer
- Freq. range : 1 – 30 MHz spectrum window is critical for cosmology
- 30x30km => 1'@30MHz comparable with XMM-Newton
- Location : Sun-Earth L2 (1.5M km) to avoid RFI and ionospheric disturbances
- Low relative drift Lissajous (or halo) orbit => low maintenance
- Loose 'passive' formation flying => baseline projections & imaging quality
- 24/7 all-sky (4pi) all-time observing => large volume of product

Ultimate-long-wavelength Sciences



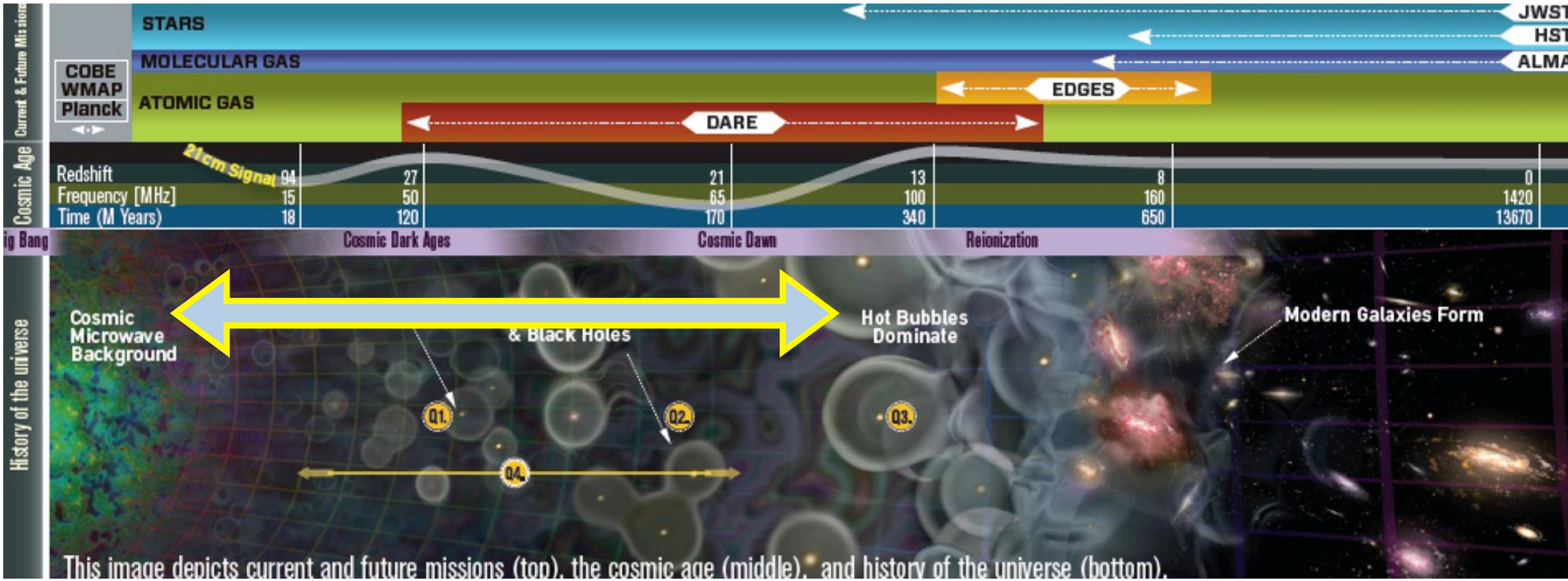
- Addresses important Cosmic Vision questions

- Primary multi-disciplinary science objectives
  - Cosmic Dark Ages using highly red-shifted 21cm emission
  - Birth, evolution and death of galaxies through cosmic time
  - The Milky Way: constituents and distribution of the ISM
  - Violent sky: monitoring/imaging of planetary radio emissions
  - Heliophysics: radio imaging of the Sun, solar flares, and CMEs

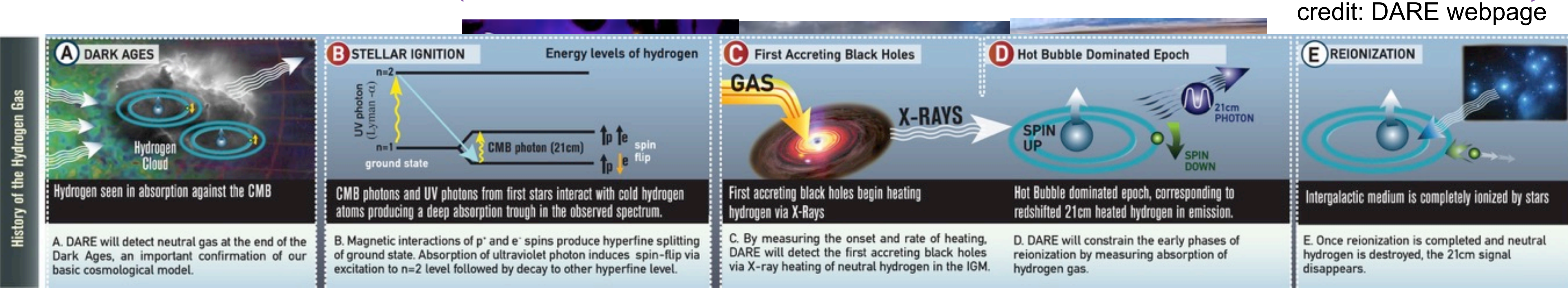
- Complement other space missions with high-res radio imaging
- Complement ground-based facilities (21CMA, LOFAR, MWA, SKA)

- Completely unexplored frequency window => unforeseen discoveries

History of the Universe

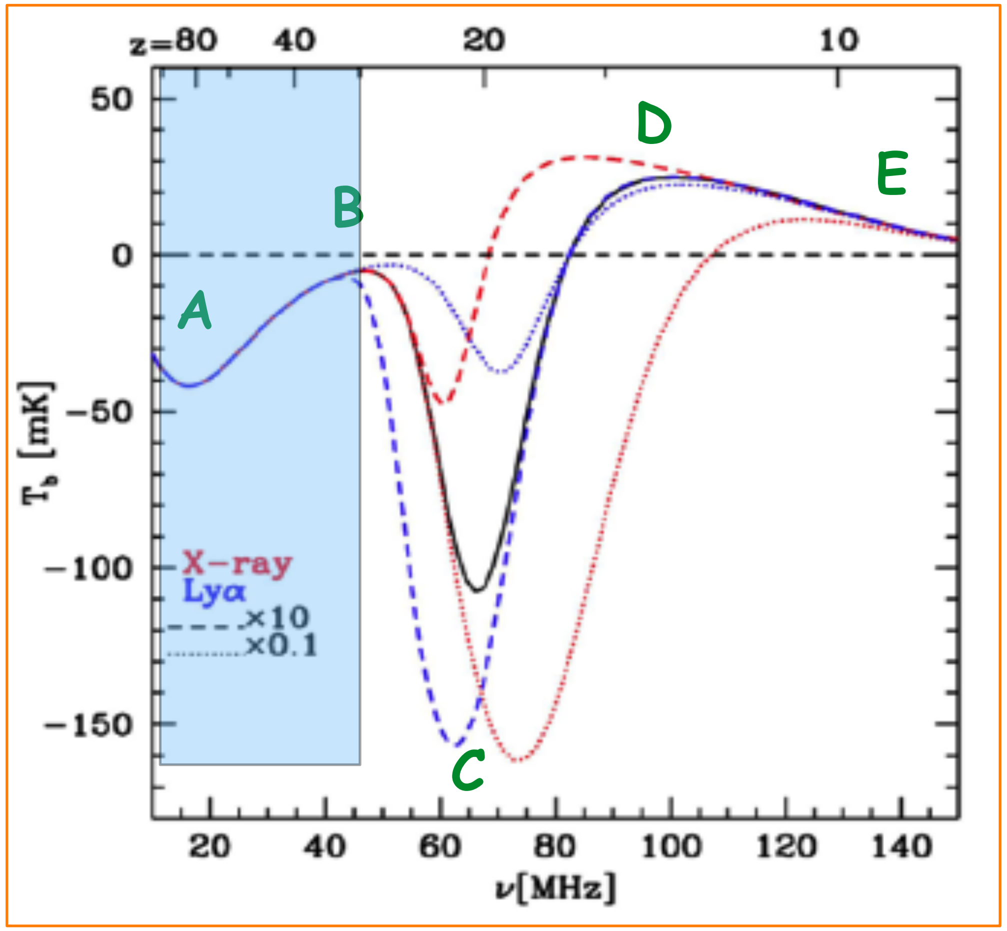


credit: DARE webpage



Cosmic Dark Ages Exploration

- Accurate tracker of the ionization history during Dark Ages of the Universe
  - Phase A: dark ages => fluctuations of the 21cm signals
  - Phase B-D : frequencies and slopes of the turning points (B-D) in the 21-cm spectrum => the onset of the first stars and black holes => when first stars and first galaxies form
- Completes the story after ground-based experiments
  - LOFAR, 21CMA, MWA, SKA: re-ionization (phase D)



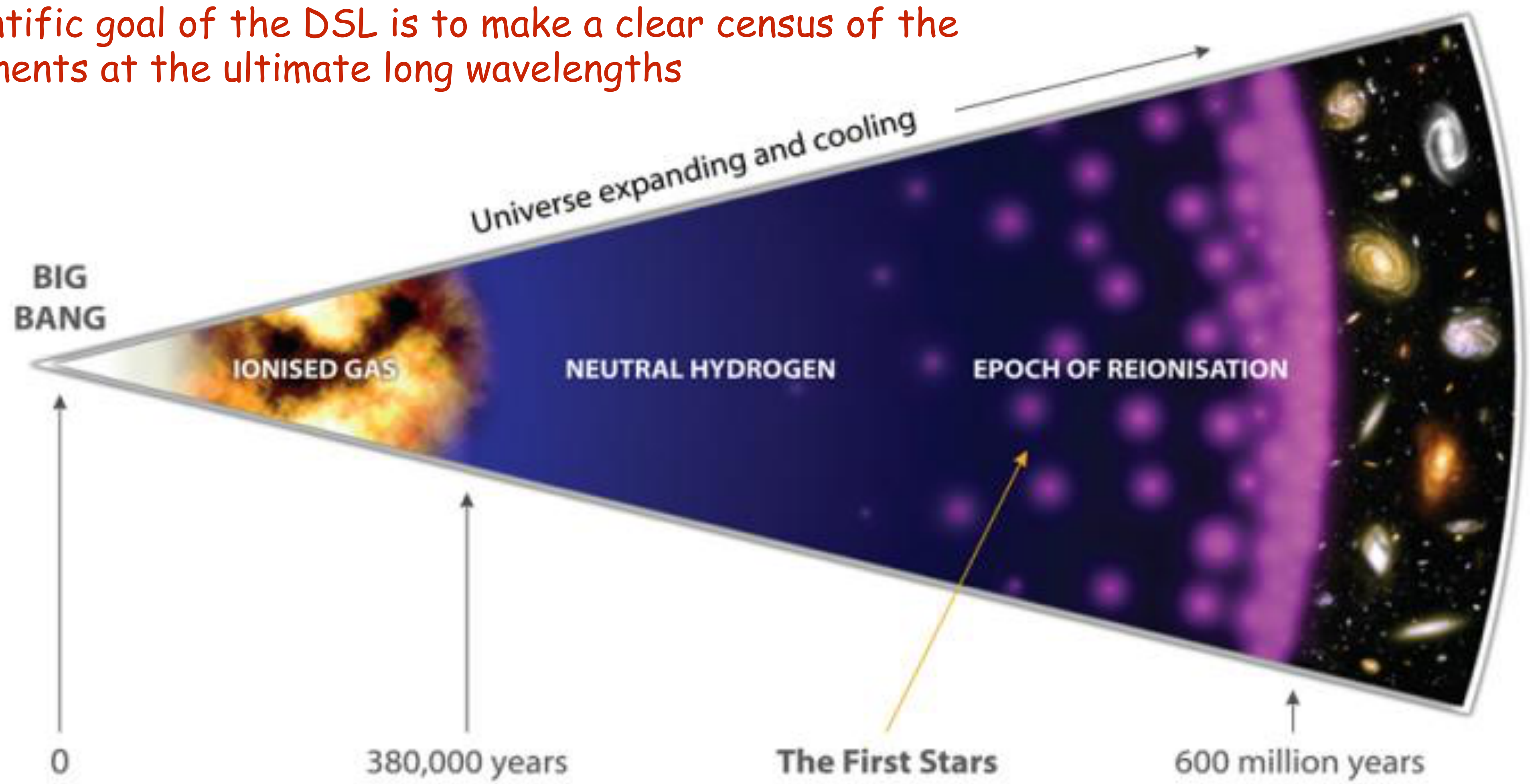
60 uK in 1 month at 30MHz in the WBS mode

- **Origin of Universe**
  - signals from EoR and dark ages
  - beginning and conditions of the early Universe

Foreground

- Extragalactic discrete radio galaxies (radio galaxy, normal galaxy)
- Violent objects in MW and in Solar system (Planets, GRBs, SNa, pulsars, XRBs …)
- Milky Way (ISM)
- Galaxy clusters, relics

An important scientific goal of the DSL is to make a clear census of the foreground components at the ultimate long wavelengths

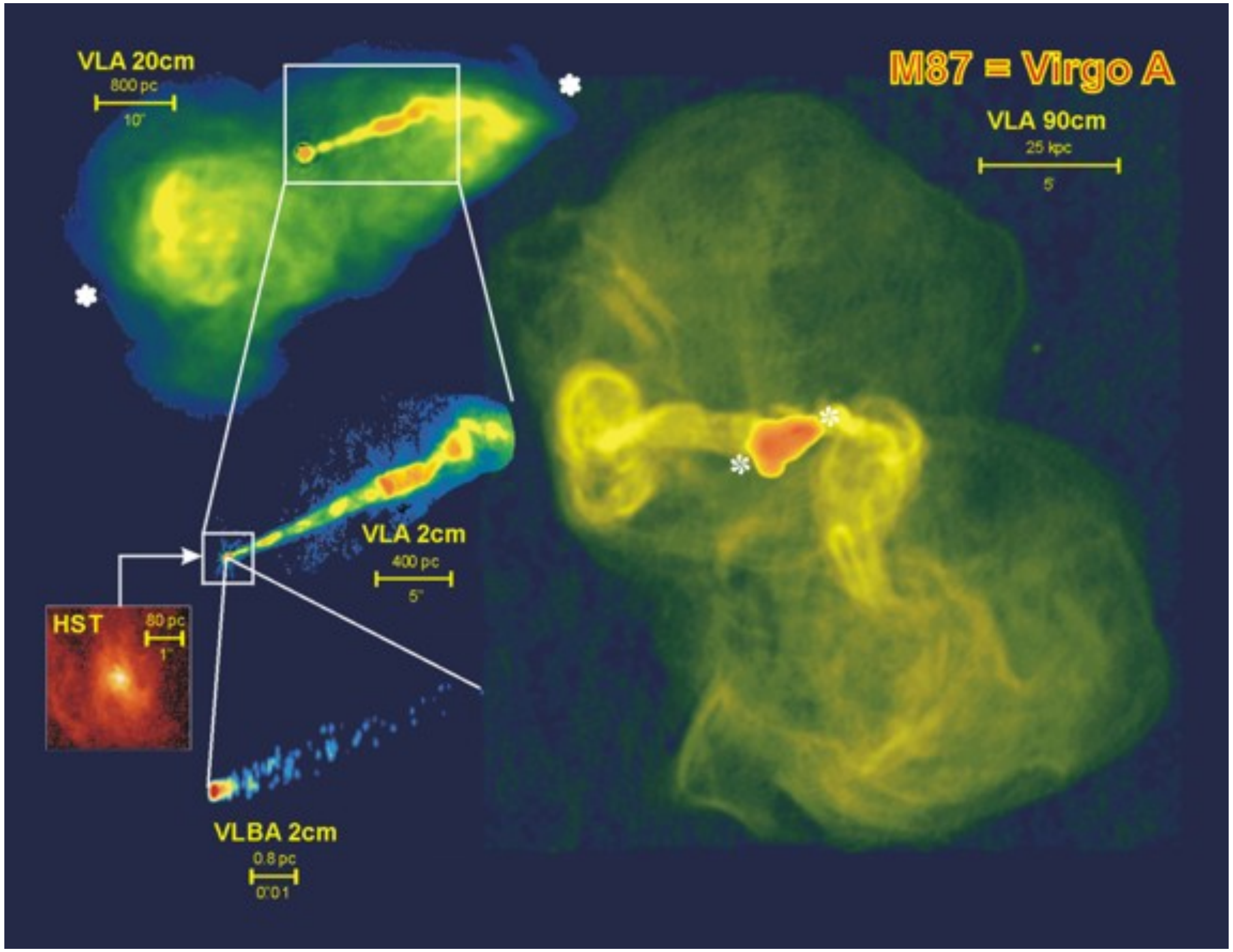


Secondary Scientific Objectives

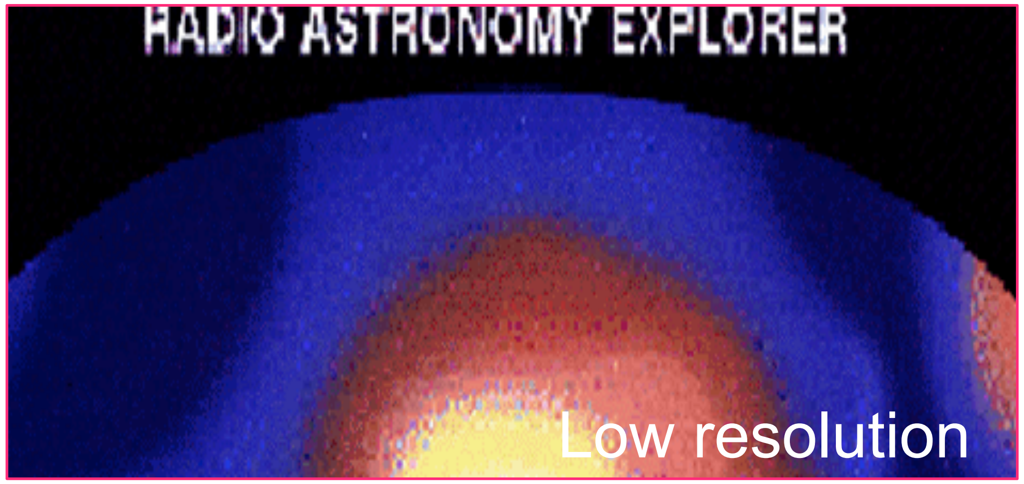
- Birth, evolution, death of radio galaxies

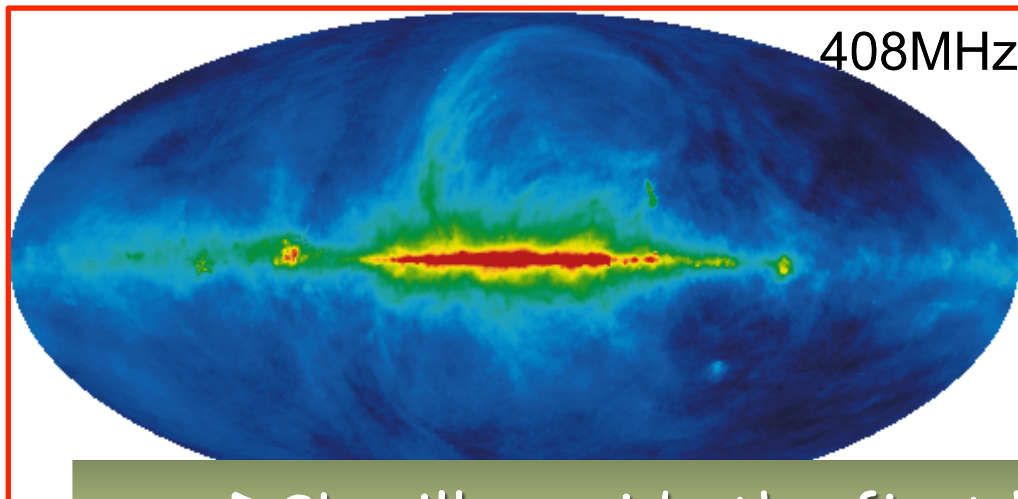
Source populations & evolution with time
Startup and death of sources
Feedback of Active Nuclei
Relics of radio sources & cool holes in clusters (10^5 sources)

See also Xuelei and Willem's talks

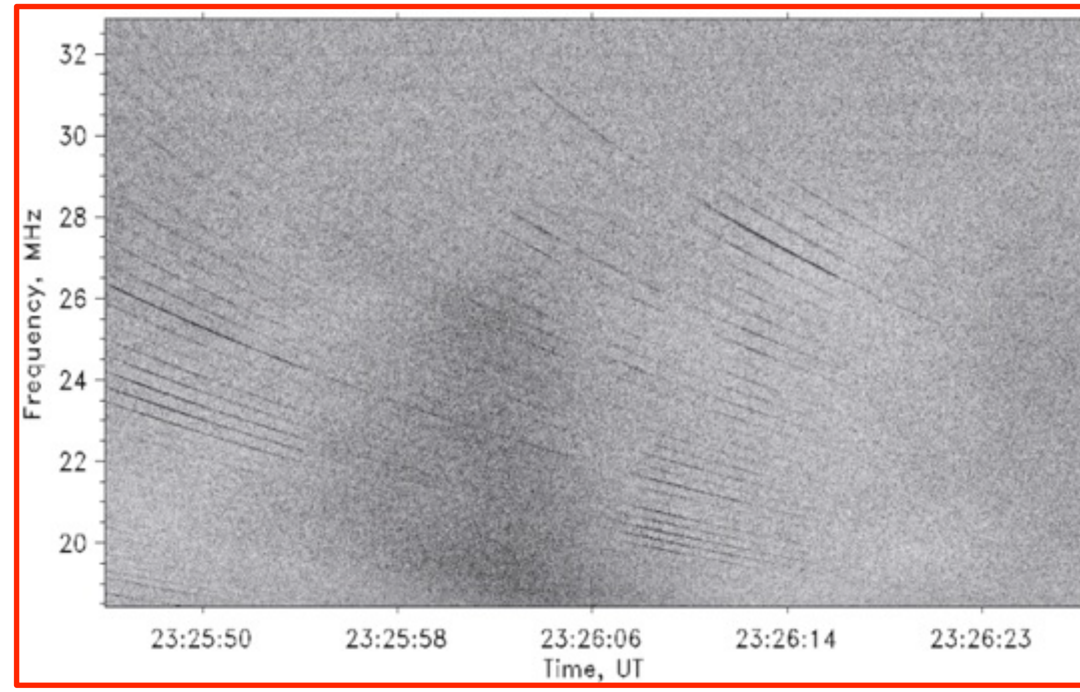


Galactic magnetic field, interstellar medium, pulsars





aslam et al 1982

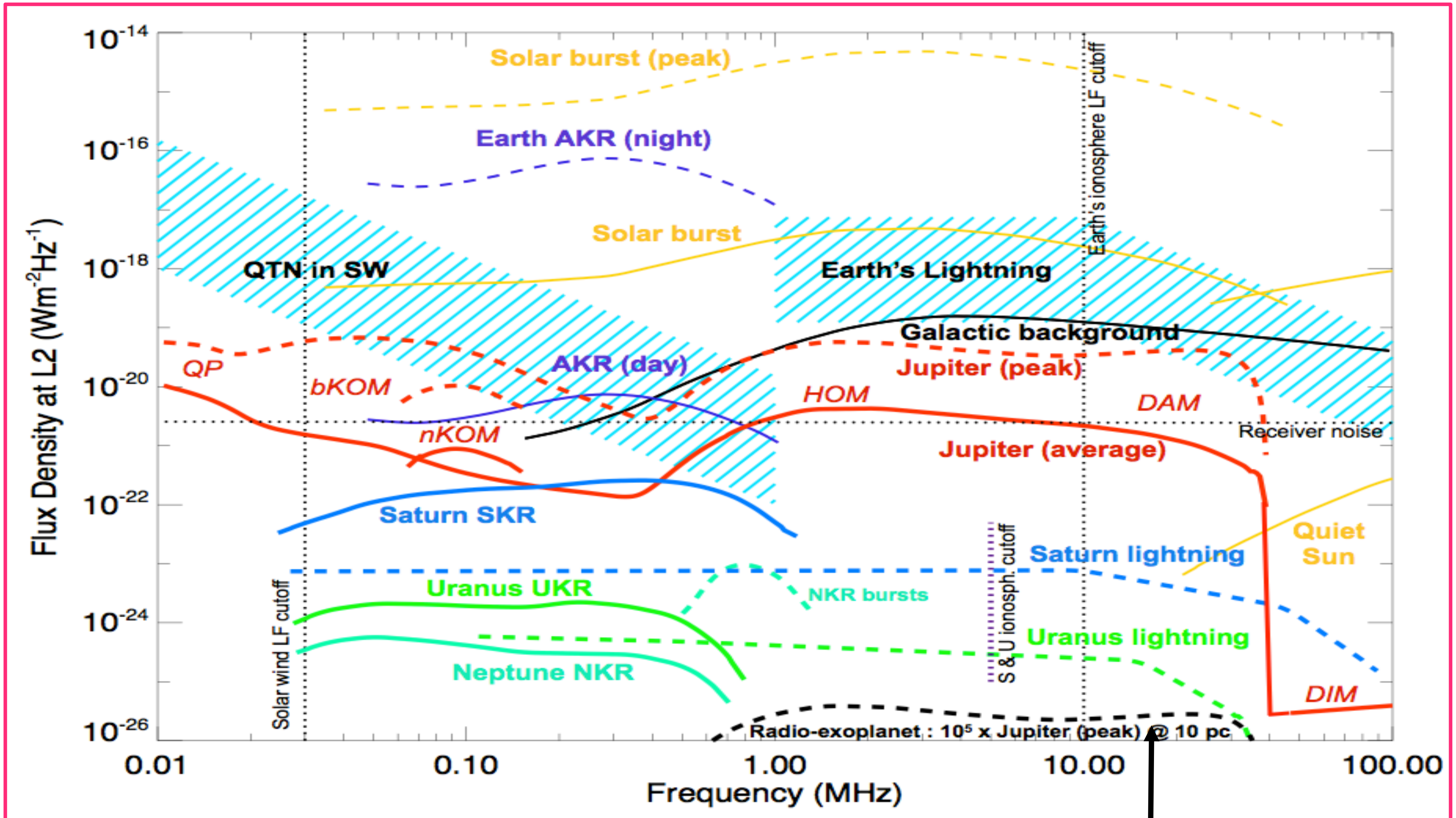


Terrestrial detection of pulsar at low freq (Kharkov)

DSL will provide the first high-resolution sky map below 400MHz

Galactic Interstellar Medium (Clumpy-Warm-Ionized)
3D Origin of Cosmic Rays – nearby HII & SNR sources
Radio Recombination Lines - also foreground for EOR
Strong pulsars – low frequency properties & spectral turnovers
Radio Transient phenomena (Baptiste Cecconi's talk)

Planetary Studies



Radio Planets & Space weather – Earth, Jupiter, Saturn & Uranus

Complex spectral structures in 0.1 – 20 MHz range

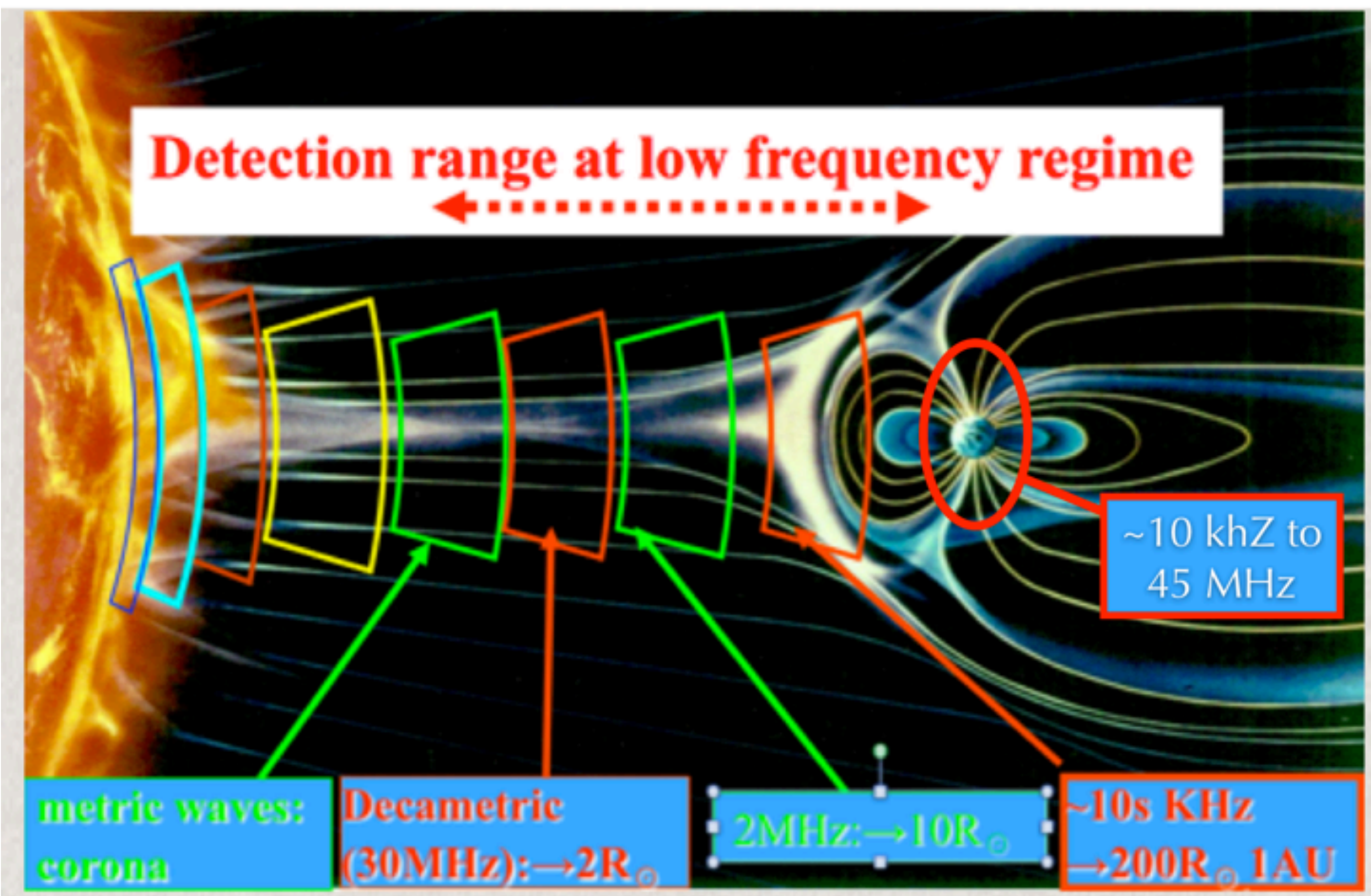
Search for Jupiter-like Exoplanets in known systems

Imaging requires long interferometric baselines

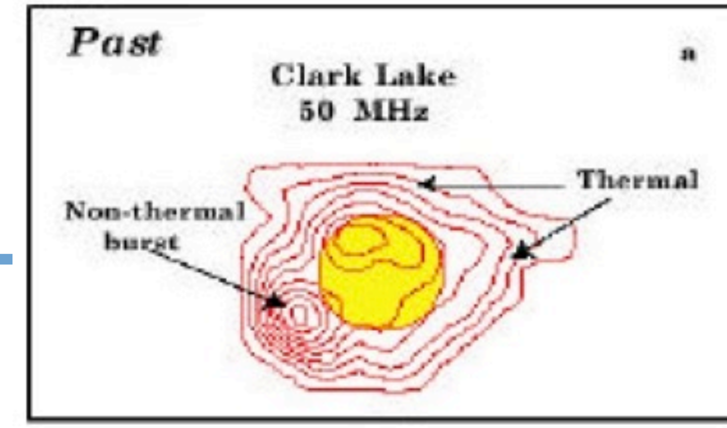
(Julien and Hanna's talks)

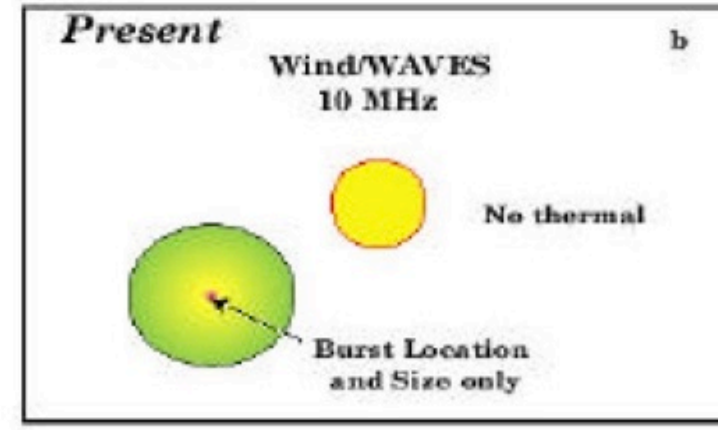
HelioPhysics & Space Weather

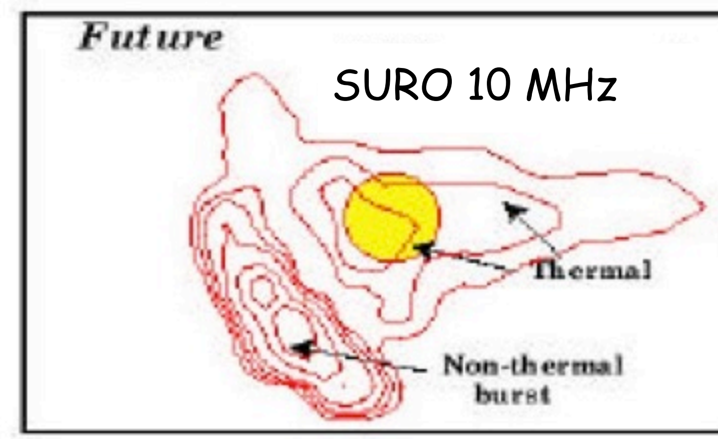
Imaging Solar activity at lower freq (3′ at 10 MHz)
Imaging Type II (slow) & III (rapid) bursts
Imaging and tracking of CMEs to larger distances
Resolution complementary to ground based arrays

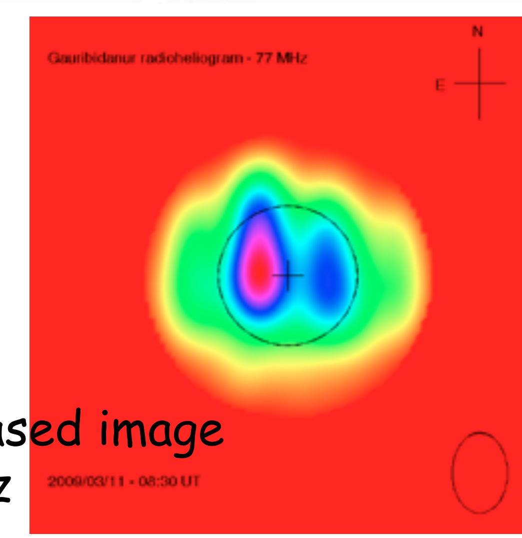


DSL will complete the CMEs over a scale of 1AU







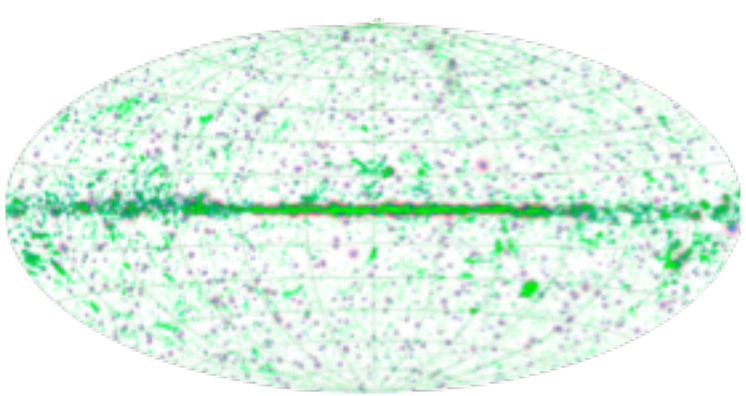


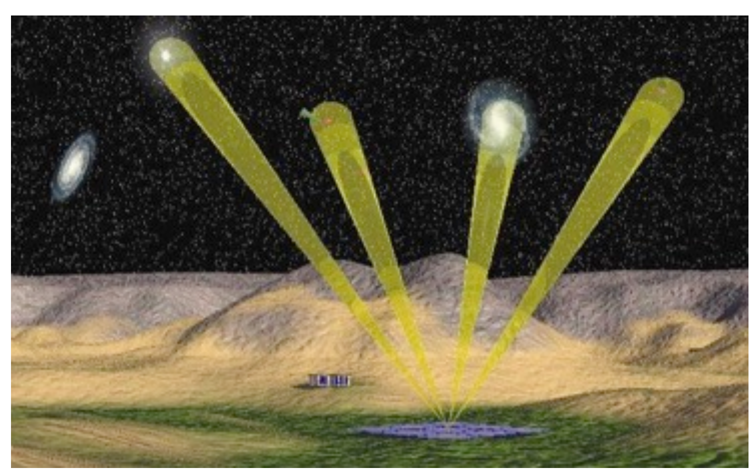
Ground-based image
at 77 MHz

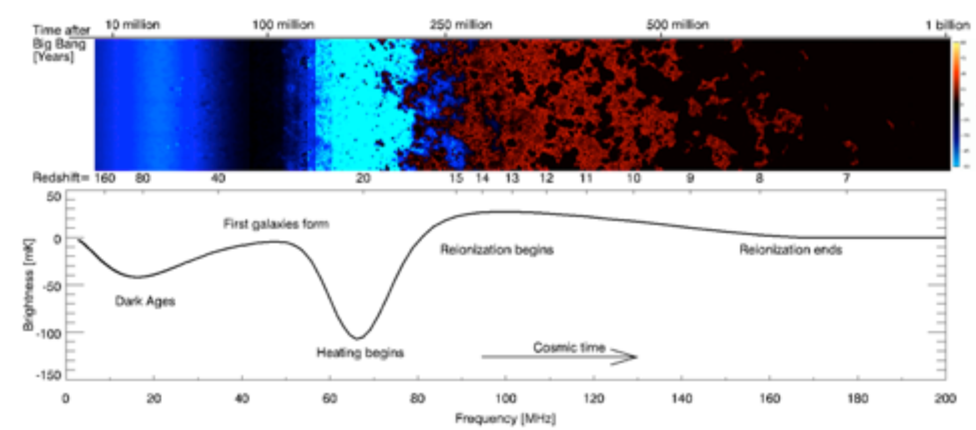
How - Observing modes

- DSL is a multi-faceted science mission supporting broad communities
  - all-sky imaging survey
  - targeted burst monitoring
  - wide band spectroscopy

- galaxy survey
- radio-loud AGN
- ISM of MW
- transients
- cosmology







All-sky compact source survey: Sensitivity

Observing Frequency	Angular Res. (arcmin)	Sensitivity 1day (mJy)	Sensitivity 1yr (mJy)	confusion limit (mJy)
70	0.49	130	7	
30	1.14	200	13	40
10	3.44	400	20	210
1	34.4	470	27	

Omni-directional Imaging of All Sky
3 arcmin at 10 MHz & 20 mJy sensitivity
1 arcmin at 30 MHz & 13 mJy sensitivity
extrapolation from source counts at 74 MHz in the VLA Low-Frequency Sky Survey (Cohen et al. 2004):
=> Detect 2 million sources in 1 yr

$$\Delta S_\nu = \frac{2kT_{\rm sys}}{A_{\rm e}\sqrt{n(n-1)\Delta\nu\tau}}$$

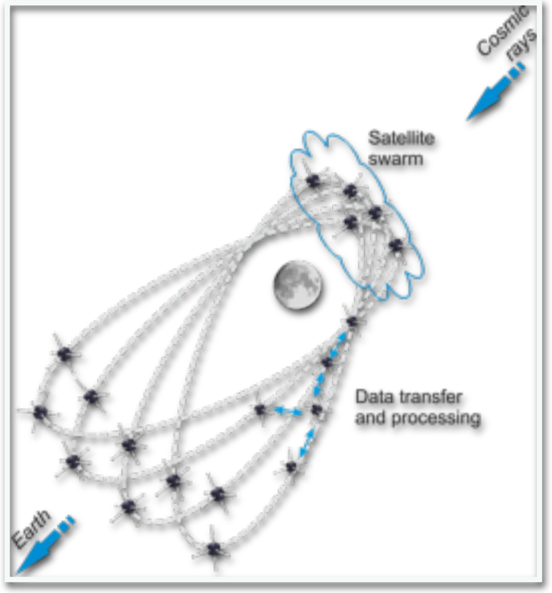
see also Willem and Maohai's talks

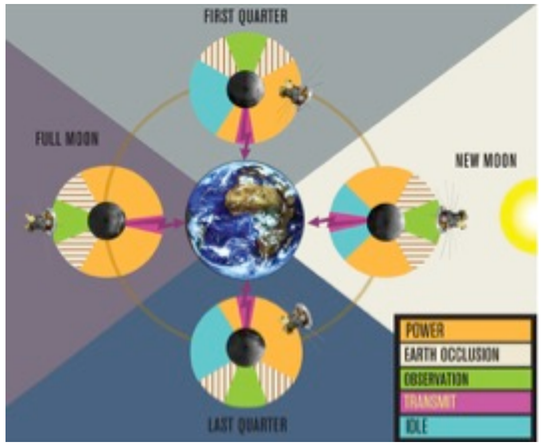
Scientific impacts — unforeseen discoveries

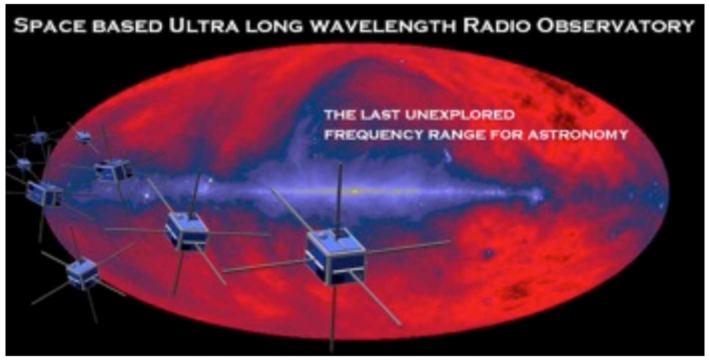
- DSL-L2: important Cosmic Vision (ESA) and Astrophysics Roadmap (NASA) question
  - Origin of Universe — How did the Universe begin and what is it made of?
  - Origin of life — What are the conditions for life and planetary formation in Universe?
  - Origin of Solar How does the Solar System work?
  - What are the fundamental physical laws of the Universe?
- Primary objective — exploration of red-shifted 21cm signals from the Dark Age
  - EoR is current highlight, but Dark Ages will be hottest in next decade
  - Exploration of Dark Ages is just a start
  - Low frequency radio: one of the three tools, probably the most effective
- DSL-L2 supports other space missions with high-res radio imaging
- DSL-L2 will cross calibrate ground-based facilities (21CMA, LOFAR, MWA, SKA, ….)
- DSL-L2 will make completely new and unforeseen discoveries - this happens each time a new frequency window is opened

Heritage

- Major concern of VLF: avoid man-made interference (RFI)
- Far enough from the Earth
  - Three separate passive formation flying ESA studies => 'feasible'
  - FIRST Explorer (2009) , DARIS (2010)
  - SURO-LC (2012): first low-cost, low-weight ULF space interferometer concept
- Shielded Zone of the Moon: back side
  - Moon orbit
    - OLFAR concept (2013, NL)
    - DARE (US) 40-120MHz
    - DAIA (2014) 0.1-30MHz
  - landing on the Moon = too expensive
- "Active" formation flying - Long history of "low-frequency space arrays"
  - Concept studied since mid 1980's.
  - Solid science case, but all proposals failed: technically infeasible or too expensive
- "Passive" formation flying
  - looser control requirements makes satellite formations technically feasible & affordable
  - Tech demo flights => Toronto U & FACE (ESA), SECM







Launching scheme

Long March 2D or Vega-class launch => Sun Earth L2

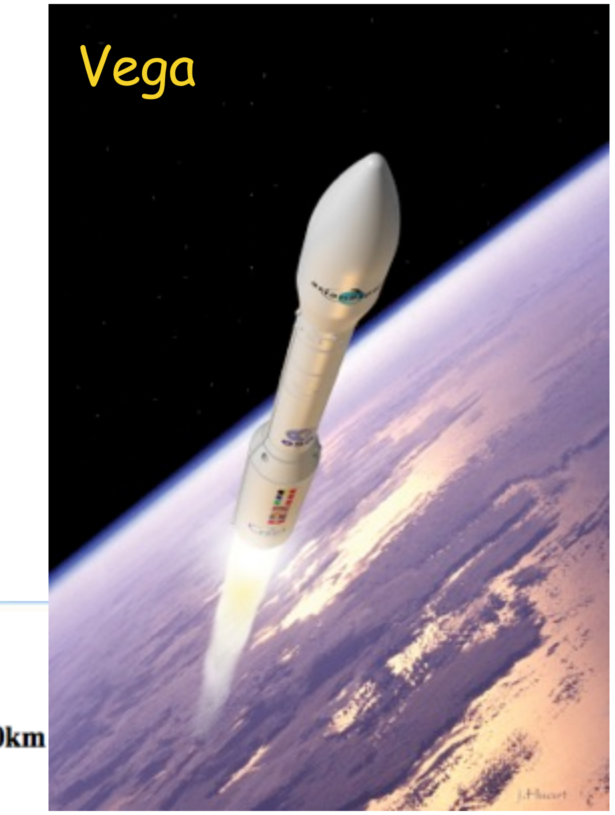
- Mothership => minimised MiniSat
- 12 Daughters => minimum NanoSat

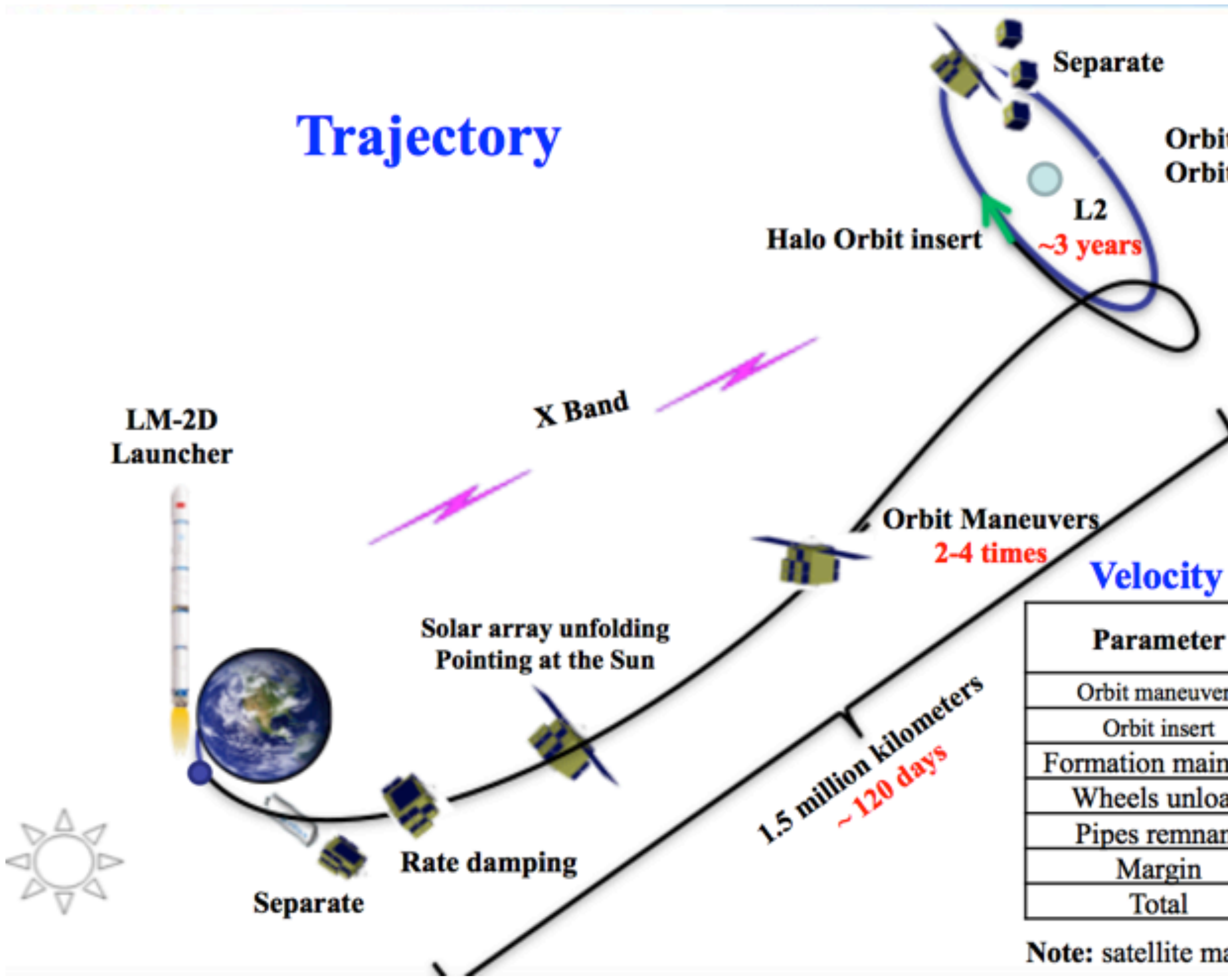
Disturbance free deployment into 30 km (moving) swarm

Loose formation flying – (reduced) swarm control & collision avoidance

Radio interferometry with sparse array (extensive experience)

Operations for 2 years (extendable to 3)

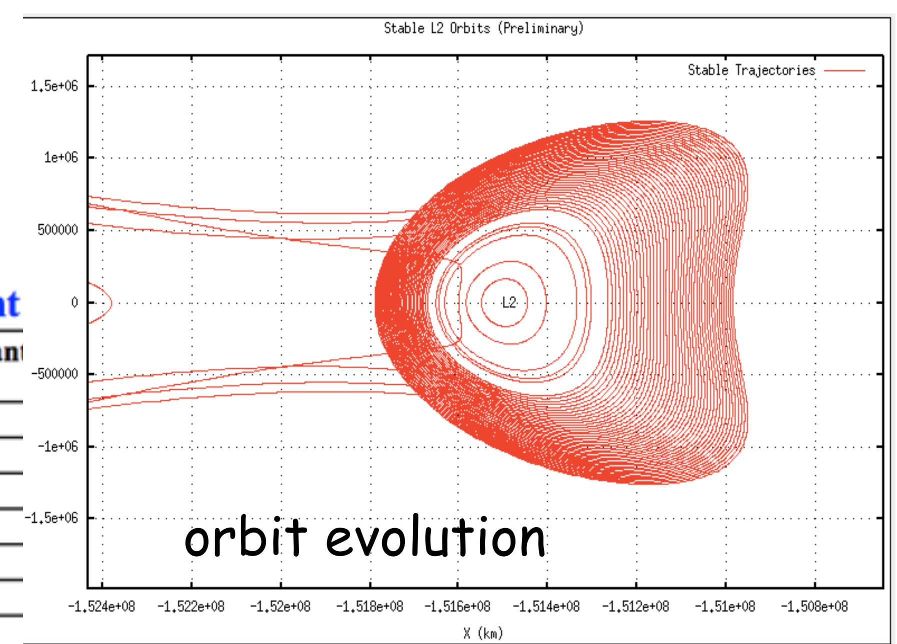




Velocity and propellant requirement

Parameter	Velocity (m/s)	Impulse (s)	Propellant (kg)
Orbit maneuvers	80.00	220.00	7.28
Orbit insert	35.00	220.00	3.10
Formation maintain	30.00	220.00	2.62
Wheels unload			3.51
Pipes remnant			0.82
Margin			3.67
Total			21.00

Note: satellite mass ~200kg; Margin ~20%

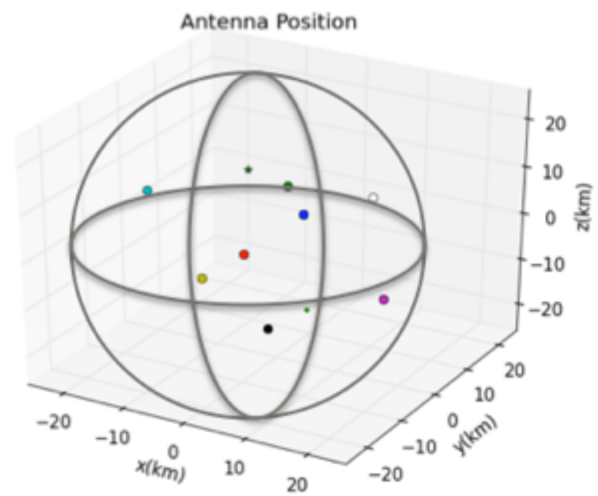


Comparison with L2 and Moon orbit

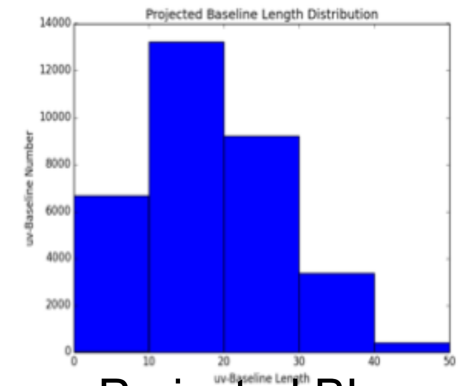
	Halo orbit in L2	Moon orbit
Velocity requirement (3 years)	145 m/s	1000 m/s
Propellant (3 years)	21 kg	100 kg (300 km×300 km)
Orbit disturbance	Small	Hard to maintain the formation
Shade	No	In 3 years, shade by Moon from both Sun and Earth: 111 days (300 km×300 km) 10 days (300 km×10000 km) 4days (300 km×20000 km)
Thermal control	Easy	Difficulty
Power balance	Easy	Difficulty
Communication	1.5 million km but longer duration	0.38 million km but having shade

Note: For Moon orbit, it has a short duration to avoid the influence of Sun and Earth to achieve the better scientific data as well as the bigger communication capacity due to shorter distance. But it need almost 5 times propellant to accomplish the mission as well as the design of thermal control and power subsystem will be more difficult.

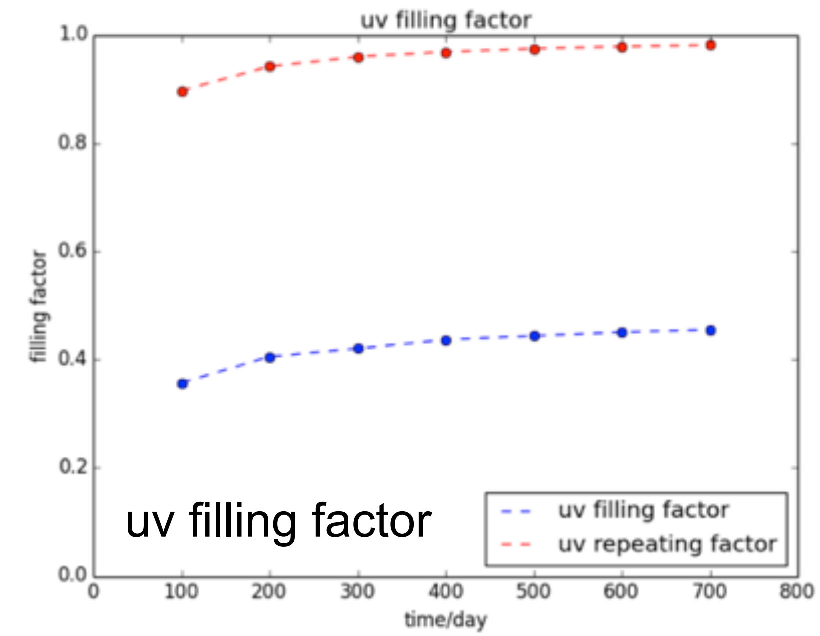
UV coverage



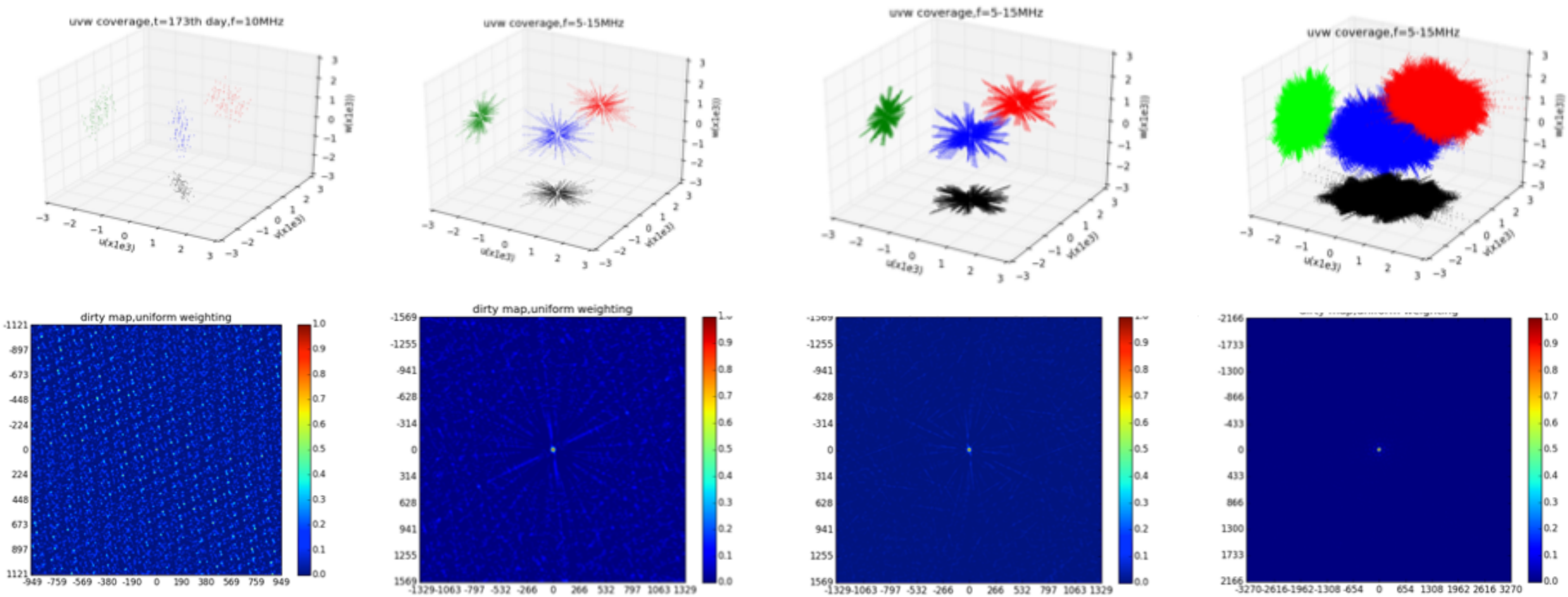
Random 3D distribution



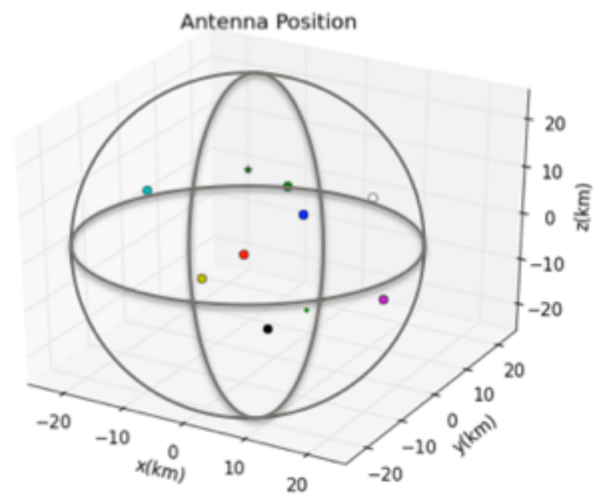
Projected BL



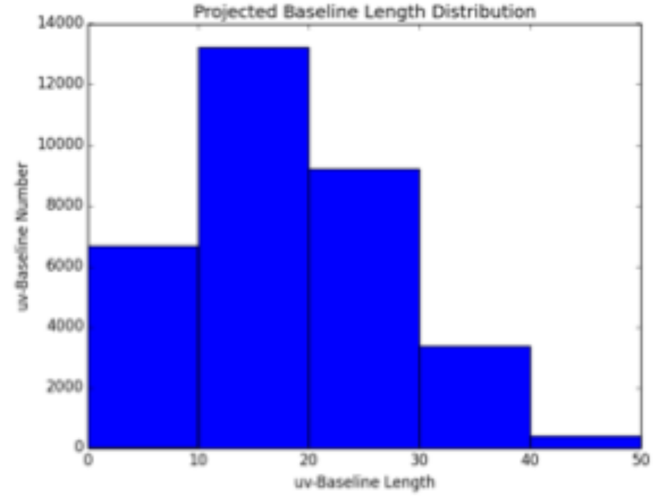
uv filling factor



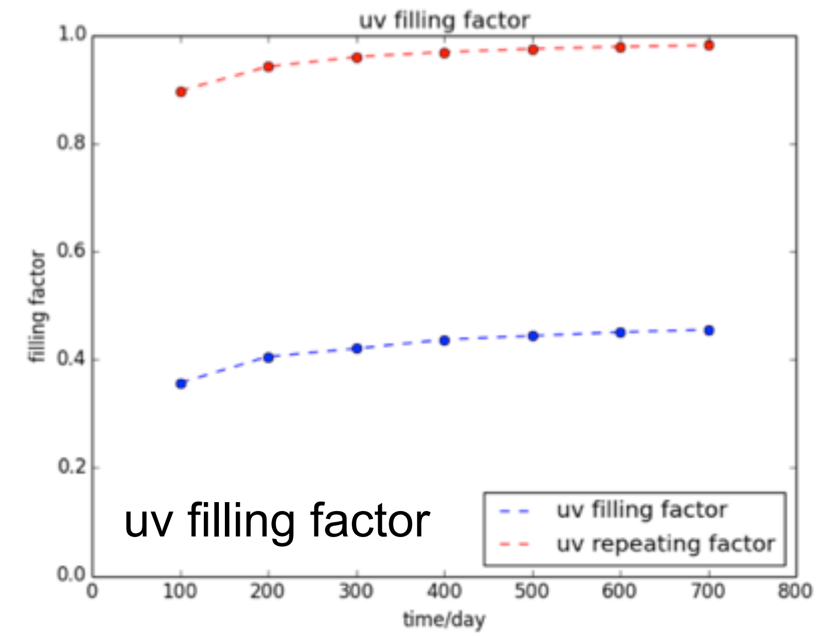
Top: uvw coverage of 1day, 1day(BW synthesis), 7day (BW syn), 1 yr (BW syn)
Bottom: PSF of 1day, 1day(BW synthesis), 7day (BW syn), 1 yr (BW syn)



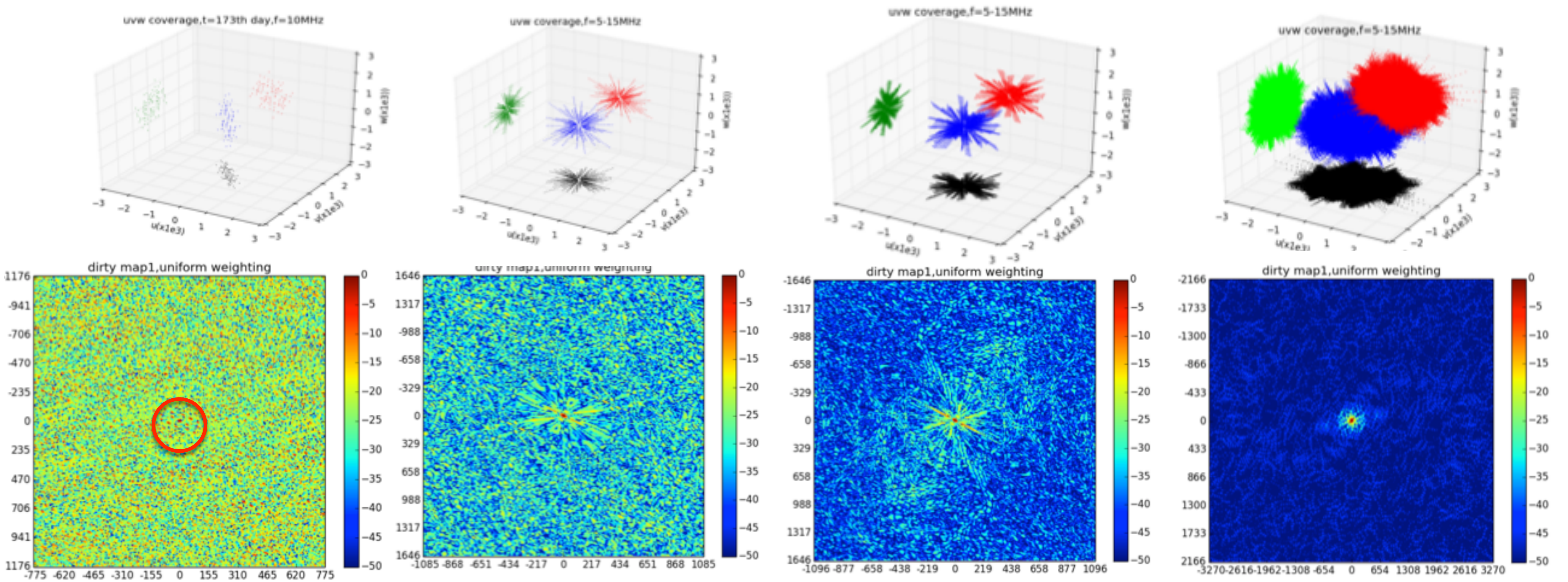
Random 3D distribution



Projected BL length



uv filling factor



Top: uvw coverage of 1day, 1day(BW synthesis), 7day (BW syn), 1 yr (BW syn)
Bottom: PSF of 1day, 1day(BW synthesis), 7day (BW syn), 1 yr (BW syn)

DSL-L2 astronomical modes

Imaging, surveys, all-sky
- Correlation of (1-bit) raw data from satellite nodes
- Integrated to 1 s (possibly10 s), sent to earth for calib. and imaging
- Full Stokes polarimetry
- All-sky imaging, based on narrow-band assumption

Transient detection, all-sky
- Standard 1s mode
  Extragalactic transients, typical timescales ~ second (due to ISM)
- Fast mode
  "Nearby" fast transients can be detected, trade-off df and dt

Transient detection, reduced FOV
- Phased-array mode to obtain high time resolution spectra

Calibration
- Using adapted versions of standard calibration approaches

Satellite platform

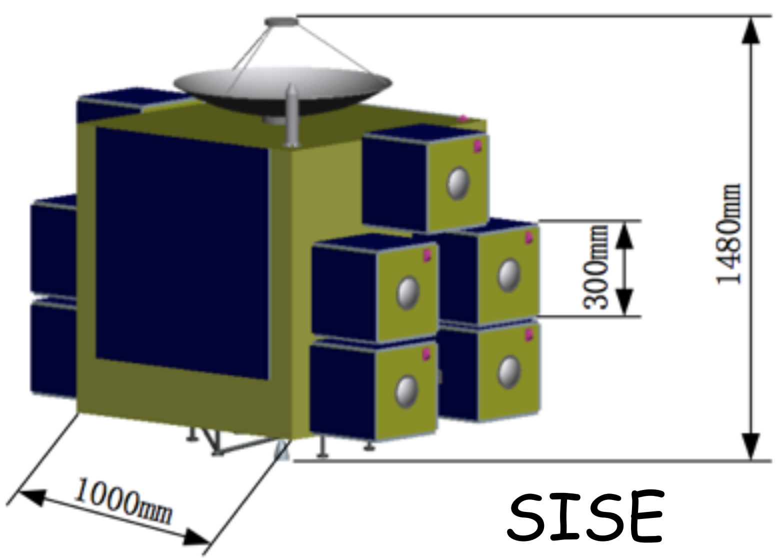
Stripped MiniSat and NanoSats

Solar Wind stabilization Daughters and Mother

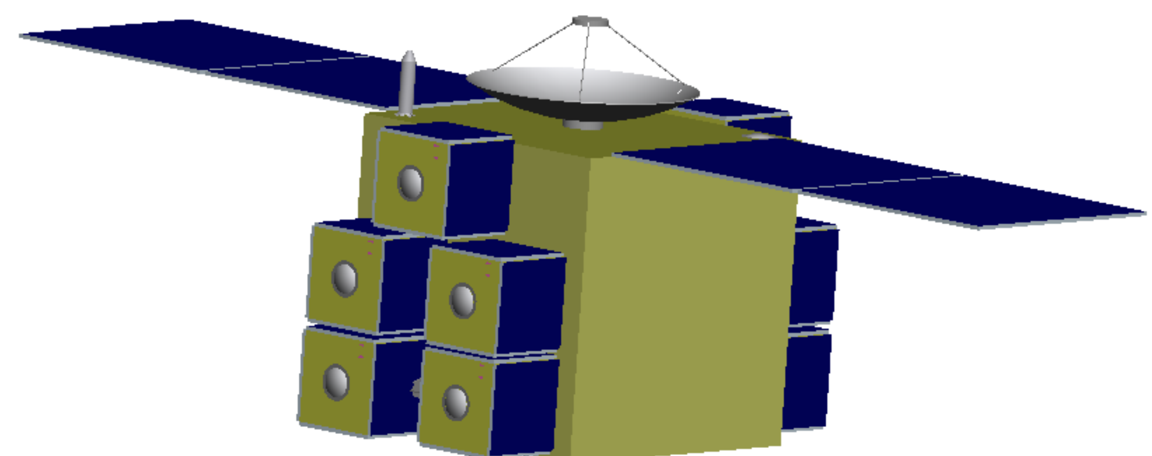
Disturbance-free deployment

Thrusters for orbit corrections within group

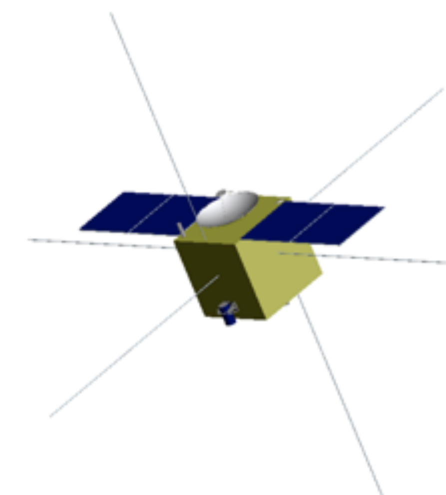
Weight <250kg = 140Kg+12x8Kg
Power < 450W
lifetime > 4yr
Reliability > 0.7

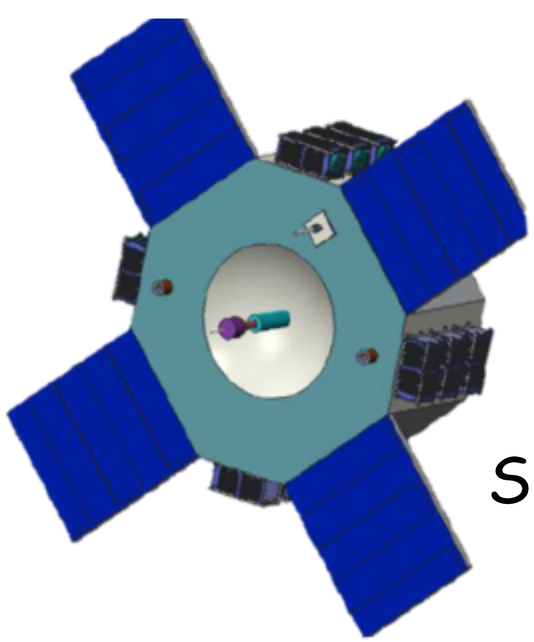


SISE

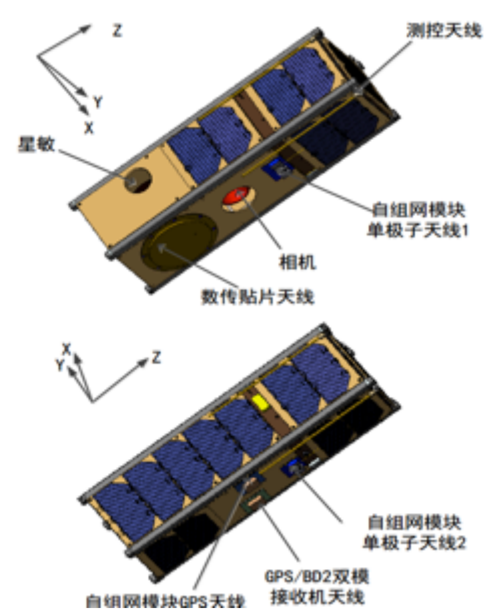


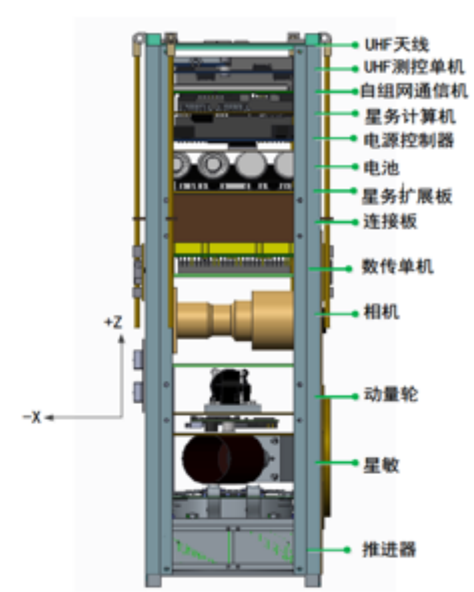
SAST100 concept (SHA Inst. Sat. Eng. 509)





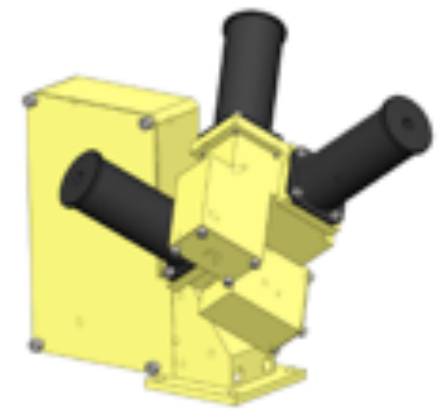
SECM

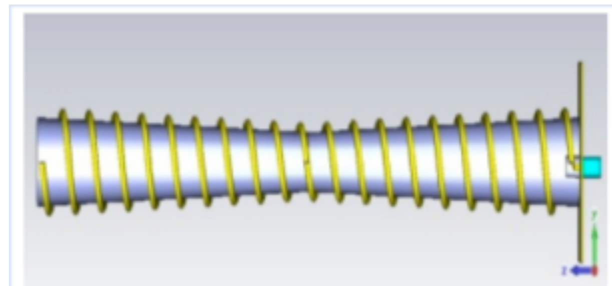


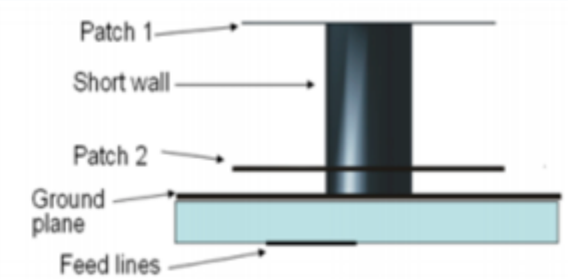


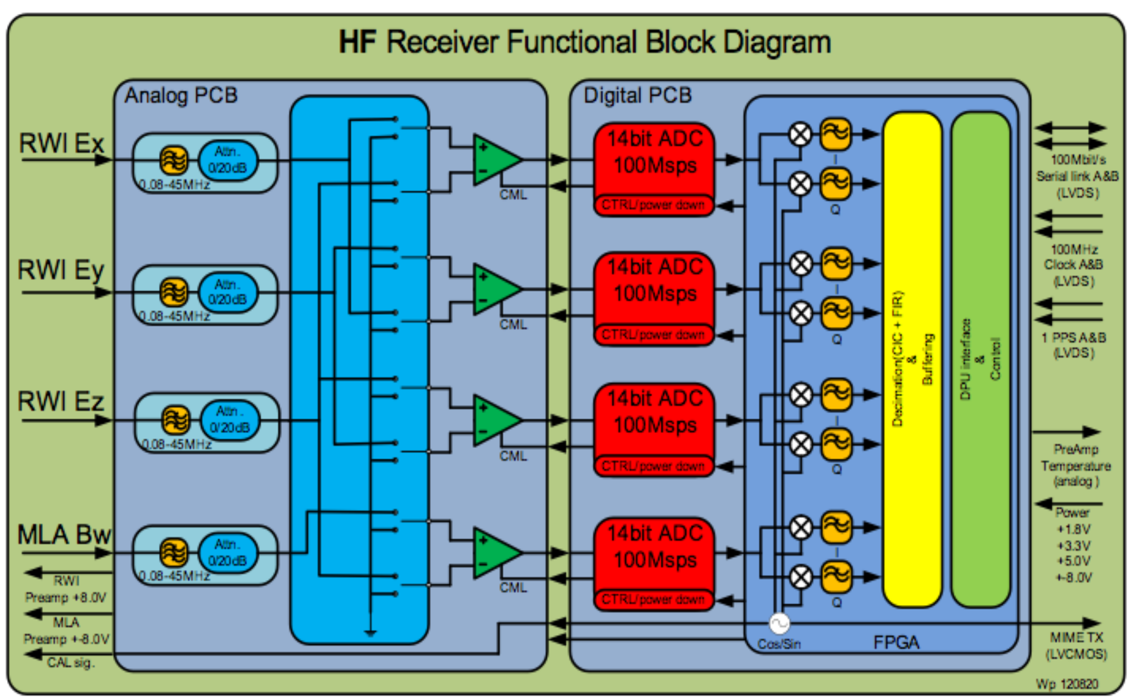
payloads

- 3 orthogonal antennas for omni-directional observing
- inter-satellite ranging & position determination
- inter-satellite data links
- on-board (distributed) processing
- Sat-Earth communication by Mother

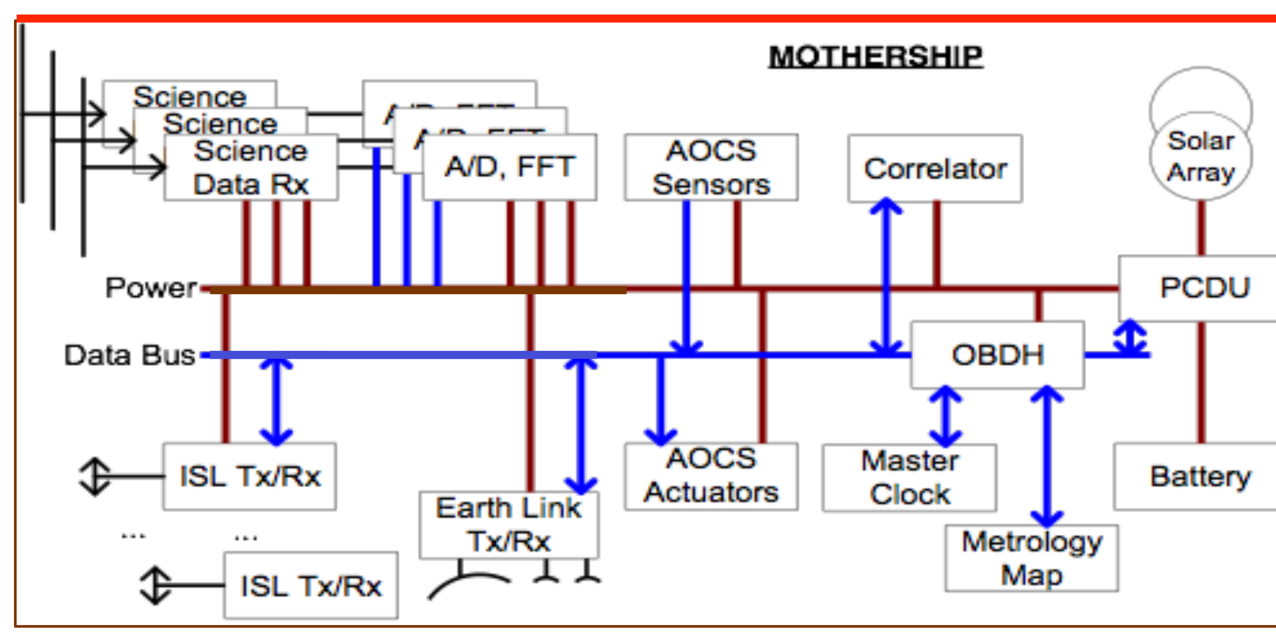






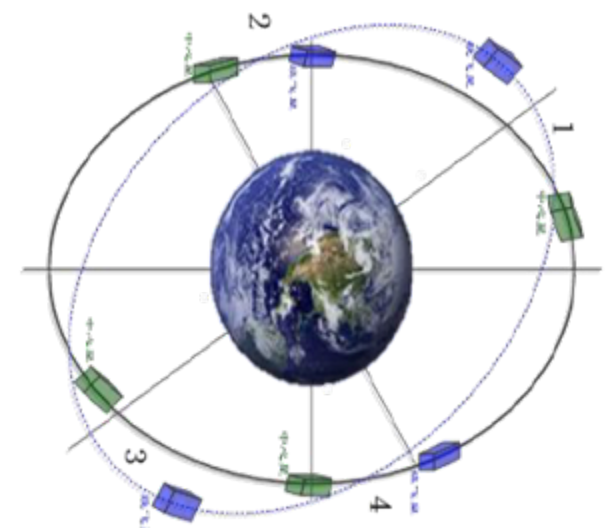


Receiver design used for ESA JUICE Mission

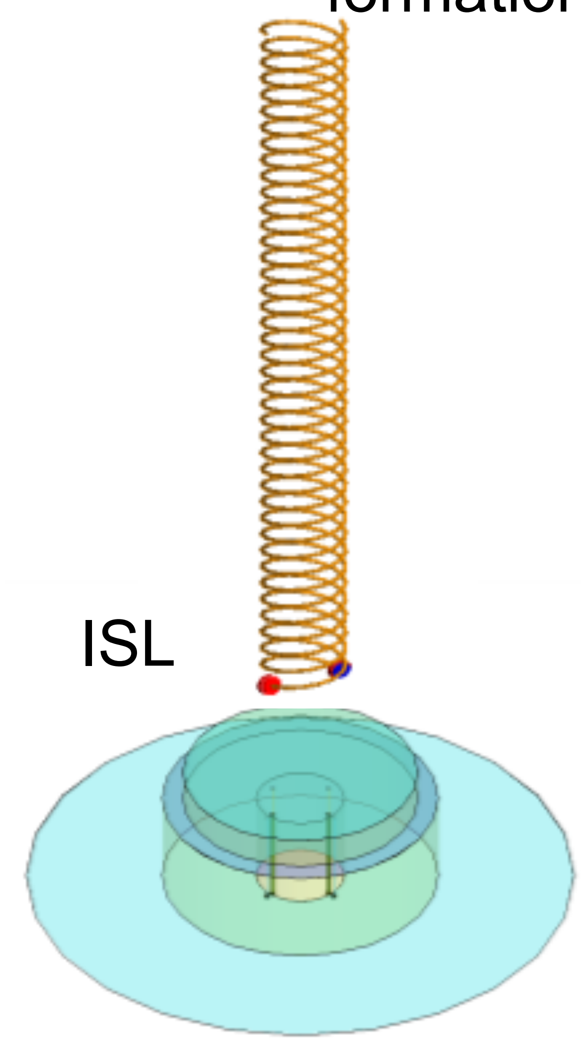


Key technologies

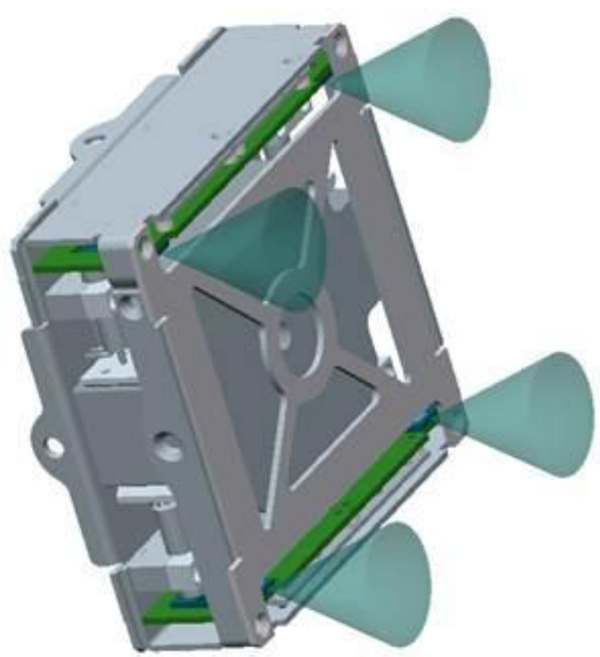
- Disturbance-free release/deployment
- Passive formation flying, constellation maintenance
- Intersatellite ranging, orientation, attitude determination
- High speed intersatellite link for wide-band observations
- Microthrust
- Measuring and controlling
- Data downlinking
- Onboard EMC



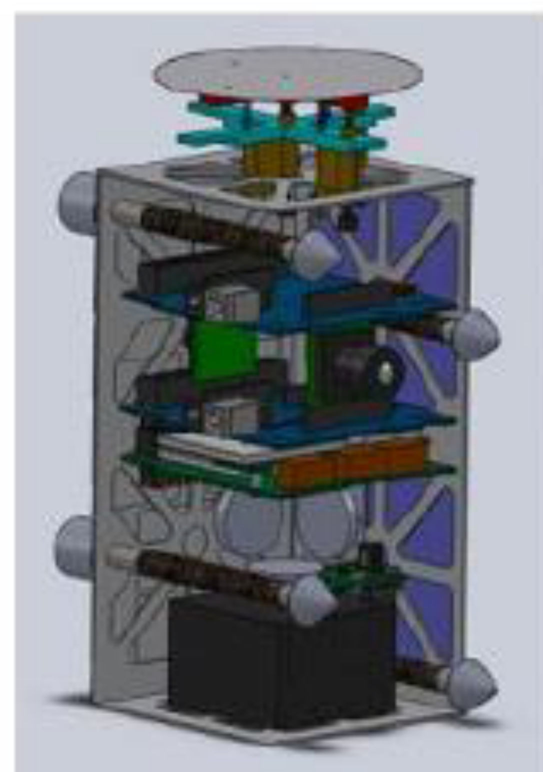
formation flying



ISL



microthruster



deployment

RFA radio frequency analyser

Frequency resolution 10kHz
time resolution for waveform 25 ns

Parameter	Value
General	
Mass [kg]	1.3 (+10% / - 30 %)
Power [W]	10.0 (+20% / - 30 %) - full operational ~2.5 (+25% / - 50 %) – standby (TM Dump)
Supply voltage [V]	28.0 (+/- 4 [V])
Dimension [mm]	190.0x160.0x92.0 (TBC)
Functional	
Number of channels	3 for E-field components
Frequency range	50.0 [kHz] to 15.0 [MHz] – E-field
Spectrum resolution	~1.0 [kHz] (50 to 1000 kHz) ~20.0 [kHz] (1.0 to 15.0 MHz)
Time resolution (wave mode)	25.0 [ns]
Dynamic range	80.0 [dB] (spectrum mode) 65.0 [dB] (wave mode)
Operational	
Discrete commands	NONE
TM/TC interface	RS 422
TC stream	2 - 3 commands/session (orbit)
TC packet length	16 bytes
TM stream	~2 - 4 kB/ sec
TM packet length	256 byte
Internal memory buffer	2MB (minimum ~10 minutes of measurement without TM dump)

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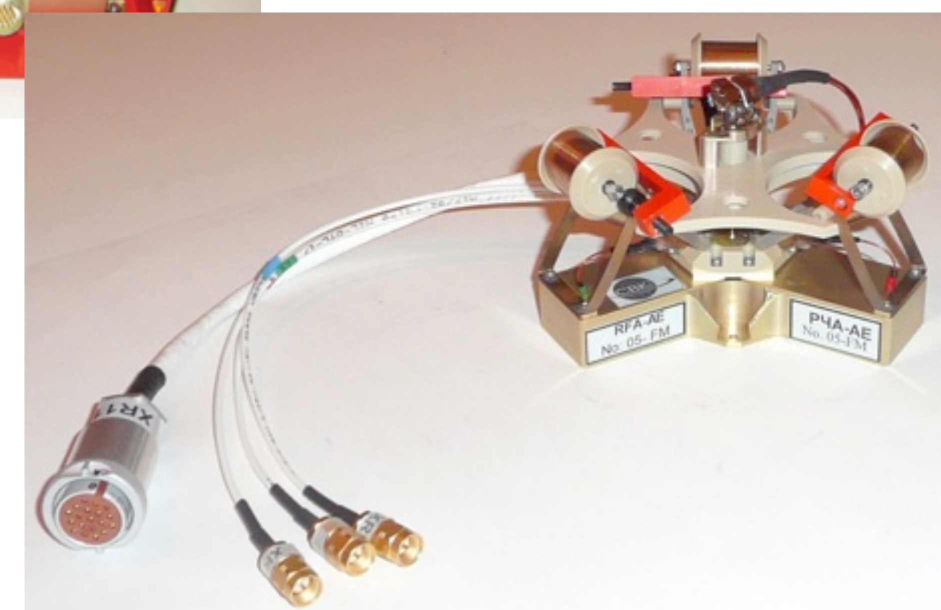

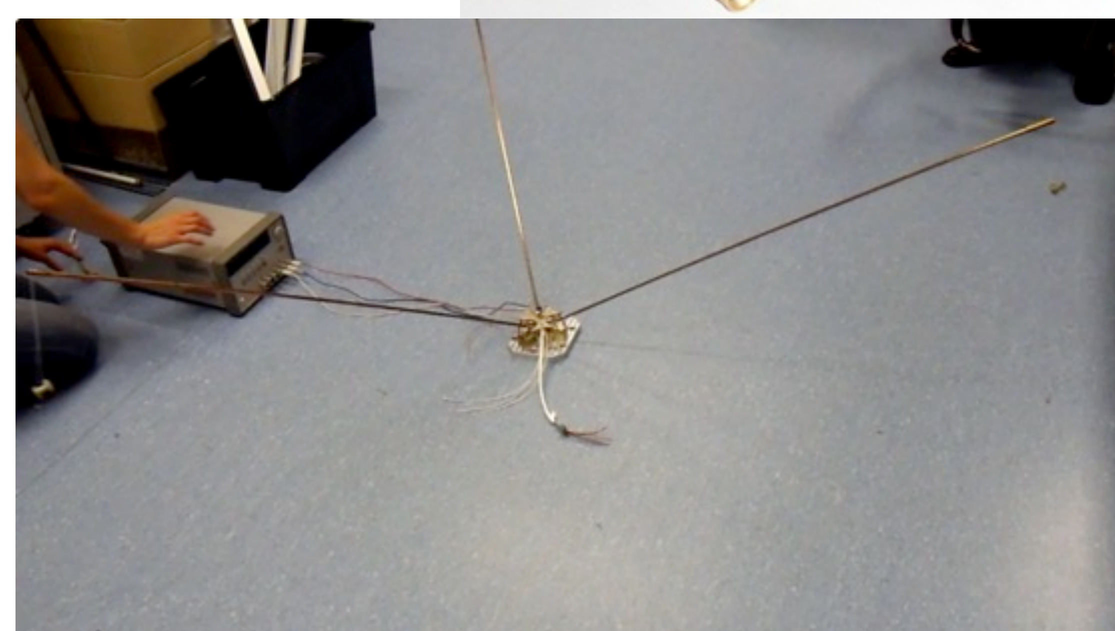

Budget

Payload	40	M RMB (5.5 M€)
Platform hardware	260	M RMB (36 M€)
Launch	80	M RMB (11 M€)
Management & operations	20	M RMB (3 M€)
Margins	60	M RMB (8 M€)
Total	460	M RMB (64 M€)

- Manufacturing period: 24Month;
- Expected launch time: 2017 if funded in 2015
- Life time : 3 yr
- Our Cost picture => lower development & production costs
- => lower for NanoSats
- => lower Chinese launch costs
- => technology readily available (high TRL)
- => China-made platforms

Summary

- An entirely new frequency window - large discovery space and prominent results
- Broad science cases — excellent collaborative project - high science return
  - astronomy, astrophysics & cosmology, space physics, space weather
- Readily available technology with high TRL - low risk
  - passive formation flying, onboard correlation, antenna & LNA, Space science instrumentation, Micro/nanotechnology etc …
- Affordable cost picture — Small/nano satellites technology - low cost
  - Pathfinder for future formation flying missions
- **Right Timing for opening the last unexplored part of the EM spectrum**