# LOFAR2.0

# A premier low-frequency array for the 2020s







## **Compared to SKA-Low Phase 1**



### LOFAR + DUPLLO

Reaches 2x lower frequency

>10x higher resolution



### **SKA-Low Phase 1**

Reaches to 2x higher frequencies

>10x higher collecting area

### What is LOFAR2.0?

- LOFAR2.0 is a staged programme of upgrades to keep LOFAR cutting edge well into the 2020s.
- Stage 1 of the LOFAR2.0 programme includes the DUPLLO and COBALT2.0 upgrades.
- Further community consultation to define possible future stages.

# DUPLLO

### Digital Upgrade for Premier LOFAR Low-band Observing



## LOFAR + DUPLLO

- Order-of-magnitude increase in sensitivity in the 10-90MHz band by maximising the use of existing infrastructure.
- Deliver a major and broad science harvest through a deep all-sky survey and other observations.
- H2020 LOFAR for Space Weather design project. DUPLLO sets the stage for turning LOFAR into a 24/7 space weather monitor.







## **LOFAR Stations**

### Robust, full-sensitivity imaging



**High-Band Antennas** 

Frequency = 110-240 MHz Wavelength = 1-3 metres



### Sensitivity and accuracy limited by ionosphere



Low-Band Antennas Frequency = 10-90 MHz Wavelength = 3-30 metres

### **LOFAR Stations**



### **Robust, full-sensitivity** imaging



**Low-Band Antennas** Frequency = 10-90 MHz Wavelength = 3-30 metres



The Moon (for comparison)

All-sky map that is unique for the next 20 years.

Provides a monumental legacy data set for the astronomical community.



### Parameter space



Shimwell

### **DUPLLO delivers a monumental survey of the sky**

DUPLLO pilot survey data





DUPLLO makes this 5x more sensitive *and* more accurate

> Only LOFAR provides the necessary angular resolution

de Gasperin



When do the first stars start to shine?



Brienza on Friday

See talk by Joe Lazio

on Monday

### DUPLLO Science Goals



 How do supermassive black holes and galaxy clusters shape the Universe? See talk by Marisa



 What is the habitability around low-mass stars and can we directly detect exoplanets? Cosmic magnetism Supermassive black holes

-Early Universe

**Galaxy clusters** 

**Solar System Planets** 

Meteors

Sun

33

**Cosmic rays** 

Pulsars

Gravitational wave events

Nearby galaxies

lonosphere



Lightning

Supernovae

Space weather

Interstellar medium

### **Beyond astronomy**

Data products with broader societal relevance and applications

### Lightning



lonosphere

#### **Space weather**



### Protect satellites & power grids

### Lightning protection Systems

**High-precision GPS** 

#### **Scientifically limited**

#### High-Band



Breakthrough techniques

#### **Rich in science**



No ionospheric correction

lonosphere well modeled

#### **Scientifically limited**

#### **High-Band**



No ionospheric correction

#### Low-Band





**Rich in science** 



#### lonosphere well modeled



Breakthrough \_

techniques

#### **Scientifically limited**

#### **High-Band**



No ionospheric correction

#### Low-Band



**2x** 



#### **Rich in science**



#### **lonosphere well modeled**



Breakthrough \_

techniques

#### **Scientifically limited**

No ionospheric correction

#### **High-Band**



Breakthrough techniques

**Rich in science** 



#### **lonosphere well modeled**



#### Low-Band







## Before DUPLLO



## With DUPLLO



### With DUPLLO



## **Proof of concept**

Shown that low-band and high-band ionosphere track each other

Shown that we can derive an ionospheric phase screen from high-band data





## **DUPLLO Innovation**

#### **Scientifically limited**





#### **Rich in science**



### The stage is set...

### Timeline





### COBALT2.0

• Order of magnitude increase in online computing.

Thanks Pandey!

• Enables massively parallel observing modes.







### LOFAR Tied-Array All-Sky Survey (LOTAAS)



J0039+35 53.04 pc/cc 0.5367 s	J0059+69 63.53 pc/cc 1.1459 s	J0100+80 55.76 pc/cc 1.4936 s	J0107+13 22.02 pc/cc 1.1974 s	J0115+63 65.04 pc/cc 0.5215 s	J0121+14 17.77 pc/cc 1.3890 s
mmmmm	Why your way	Mr Karman	MM MMMMMMM	why manufacture	my hour hours
J0139+33 21.21 pc/cc 1.2479 s	J0210+58 76.70 pc/cc 1.7663 s	J0250+58 45.8 pc/cc 23.5355 s	J0302+22 19.09 pc/cc 1.2072 s	J0305+11 27.97 pc/cc 0.8621 s	J0317+13 12.90 pc/cc 1.9743 s
manuman	And Manufacture	mun man man	Mr. Myn My winner	my moundar	Mr. humanny
J0349+23 63.15 pc/cc 2.4208 s	J0421+32 77.0 pc/cc 0.9001 s	J0454+45 20.82 pc/cc 1.3892 s	J0518+51 39.15 pc/cc 0.9125 s	J0742+43 36.23 pc/cc 0.6062 s	J0811+37 16.95 pc/cc 1.2483 s
walter and warman	my many	mulmin	MM Mr May May	why pulling man	Man proposition
J0813+22 52.29 pc/cc 0.5314 s	J0827+53 23.103 pc/cc 0.0135 s	J0857+33 24.025 pc/cc 0.2430 s	J0928+30 21.95 pc/cc 2.0915 s	J0935+33 18.35 pc/cc 0.9615 s	J1017+30 27.16 pc/cc ∧ 0.4528 s
yn Myrmyllulin	~~~~~	MW Manner Marken	malumman	men promonent	why phonemana
J1226+00 18.50 pc/cc 2.2851 s	J1235-02 18.8 pc/cc 3.5976 s	J1303+38 19.000 pc/cc 0.3963 s	J1334+10 24.00 pc/cc 0.9111 s	J1344+66 30.02 pc/cc 1.3941 s	J1404+11 18.48 pc/cc 2.6505 s
magnoment	www.monowywww	montherman	MWY Mary Mary	why Allow Allow	multiment
J1426+52 25.37 pc/cc 0.9958 s	J1529+40 6.61 pc/cc 0.4764 s	J1623+58 26.40 pc/cc 0.6518 s	J1635+23 37.60 pc/cc 1.2087 s	J1638+40 33.35 pc/cc 0.7677 s	J1643+13 35.97 pc/cc 1.0991 s
And prover the work	Myr Wyrwhryw	my propringer	my many mark	wingprobability	when how Monthly
J1655+62 35.41 pc/cc 0.7762 s	J1657+33 24.04 pc/cc 1.5702 s	J1658+36 3.050 pc/cc 0.0330 s	J1707+35 19.240 pc/cc 0.1598 s	J1713+78 36.96 pc/cc 0.4325 s	J1715+46 19.82 pc/cc 0.5481 s
when providente	multimenter	mom	munum	mpro wannumphan	who have whether
J1722+35 23.83 pc/cc 0.8216 s	J1735+63 41.81 pc/cc 0.5107 s	J1740+27 35.46 pc/cc 1.0582 s	J1741+38 47.26 pc/cc 0.8289 s	J1745+12 66.32 pc/cc 1.0599 s	J1745+42 38.00 pc/cc 0.3051 s
mul provinger and	Ann Mannen	Mr. M.	And Marker Marken	My Mrowmy	MM VyMymmmym
J1749+59 45.09 pc/cc 0.4360 s	J1809+17 47.32 pc/cc 2.0667 s	J1810+07 79.41 pc/cc 0.3077 s	J1814+22 62.313 pc/cc 0.2537 s	J1848+15 77.42 pc/cc 2.2338 s	J1849+25 74.970 pc/cc 0.5193 s
HW WARNAM	when when when	MW & MM MMMMMMMMM	-way por manufu	www. Maraman	mm manument
J1910+56 20.75 pc/cc 0.3419 s	J1916+32 83.99 pc/cc 1.1374 s	J1933+53 33.52 pc/cc 2.0526 s	J1953+30 43.61 pc/cc 1.2712 s	J1957-00 38.31 pc/cc 0.9651 s	J1958+56 58.10 pc/cc 0.3118 s
M. Amphram	man parti man	WW WWW WWW	many personance	may my my man	MM MUNHMMMM
J2006+22 130.56 pc/cc 1.7419 s	J2022+21 73.52 pc/cc 0.8035 s	J2036+66 50.82 pc/cc 0.5019 s	J2051+12 43.40 pc/cc 0.5532 s	J2053+17 26.980 pc/cc 0.1193 s	J2057+21 73.31 pc/cc 1.1667 s
man management	why promograph	how phylinmagnite	man monologica	monthyman	may promising whe
J2122+24 8.49 pc/cc 0.5414 s	J2123+36 108.7 pc/cc 1.2940 s	J2209+22 46.30 pc/cc 1.7769 s	J2306+31 46.13 pc/cc 0.3416 s	J2329+47 43.99 pc/cc 0.7284 s	J2336-01 19.60 pc/cc 1.0298 s
men margundallet	NW WWWWWW	Marthone	my month	mannin	my mymmum
J2350+31 39.14 pc/cc 0.5081 s	0 0.5 1	0 0.5 1	0 0.5 1	0 0.5 1	0 0.5 1
muy promonent					
ע 0.5 1					

#### Sanidas et al., almost submitted

Pulse phase

ά

### LOFAR super-slow (23.5-sec) pulsar discovery





LoTSS `on' and `off' images



### LOFAR millisecond pulsar discoveries



Bassa, Pleunis & Hessels 2017 Bassa et al. 2017 Pleunis et al. 2017

### LOFAR is expanding the pulsar parameter space



DUPLLO+LOFAR will deliver the deepest and highestresolution 10-90MHz all-sky survey ever performed