## **LOFAR2.0 Science** *Jason Hessels*

LOFAR2.0 Project Scientist

# **LOFAR Stations**





#### **Sensitivity and** accuracy limited by ionosphere



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

# **LOFAR Stations**



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

**High-Band Antennas** Frequency =  $110-240$  MHz Wavelength =  $1-3$  metres

**Robust, full-sensitivity** 

imaging

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

## **Timeline**



## LOFAR2.0 Commissioning



**London Antennas, st** Antennas, stations<br>& network & network







Correlator & central processing Pipelines





LOFAR Detection of 110–188MHz Emission and Frequency-dependent Activity from FRB 20180916B Z. Pleunis<sup>1,2</sup> (B. D. Michilli<sup>1,2</sup> (B. G. G. Bassa<sup>1</sup> (B. J. W. T. Hessels<sup>12</sup> (B. A. Naidu<sup>1</sup> (B. B. C. Andersen<sup>12</sup> (B. P. Chawla<sup>12</sup> (B. E. Fonseca<sup>1,24</sup>, G. A. Gopinath<sup>35</sup>, S. M. Kaspi<sup>2, S</sup>. V. I. Kondratiev<sup>3, S</sup>. D. Z. Li<sup>9,10</sup> (b. M. Bhardwai<sup>1,2</sup> G. P. J. Boyle<sup>13</sup>, G. C. Brat<sup>12</sup> , T. Cassanelli<sup>11,12</sup> O. Y. Gupta<sup>13</sup> O. A. Josephy<sup>1,2</sup> O. R. Karuppusamy<sup>14</sup> Q. A. Keimpema<sup>16</sup> Q. F. Kirsten<sup>16</sup> Q. C. Leung<sup>17,18</sup> O., B. Marcote<sup>16</sup> O., K. W. Masui<sup>17, 18</sup> O., R. W. Meyers<sup>19</sup>, D. Ng<sup>11</sup> O., C. Ng<sup>11</sup> O., K. Nimmo<sup>1,4</sup> O. Z. Paragi<sup>15</sup> , M. Rahman<sup>11,20</sup> O. P. Scholz<sup>11</sup> O. K. Shin<sup>21, M</sup>. K. M. 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Dunlap Department of Astronomy & Astrophysics, University of Toronto, 50 St. George Street, Toronto, ON M5S 3H4, Canada <sup>13</sup> National Centre for Radio Astrophysics, Post Bag 3, Ganeshkhind, Pune 411007, India <sup>14</sup> Max Planck Institute for Radio Astronomy, Auf dem Hügel 69, D-53121 Bonn, Germany <sup>15</sup> Joint Institute for VLBI ERIC, Oude Hoogeveensedijk 4, 7991 PD Dwingeloo, The Netherlands <sup>16</sup> Department of Space, Earth and Environment, Chalmers University of Technology, Onsala Space Observatory, SE-439 92, Onsala, Sweden <sup>17</sup> MIT Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA <sup>18</sup> Department of Physics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA <sup>19</sup> Department of Physics and Astronomy, 6224 Agricultural Road, Vancouver, BC V6T 1Z1, Canada <sup>20</sup> Sidrat Research, P.O. Box 73527 RPO Wychwood, Toronto, ON, M6C 4A7, Canada <sup>21</sup> Perimeter Institute for Theoretical Physics, 31 Caroline Street N, Waterloo, ON N2L 2Y5, Canada <sup>22</sup> Department of Astronomy and Astrophysics, Tata Institute of Fundamental Research, Mumbai 400005, India Received 2020 December 15; revised 2021 March 3; accepted 2021 March 4; published 2021 April 9 Abstract The object FRB 20180916B is a well-studied repeating fast radio burst source. Its proximity (∼150 Mpc), along with detailed studies of the bursts, has revealed many clues about its nature, including a 16.3 day periodicity in its activity. Here we report on the detection of 18 bursts using LOFAR at 110–188 MHz, by far the lowest-frequency detections of any FRB to date. Some bursts are seen down to the lowest observed frequency of 110 MHz, suggesting that their spectra extend even lower. These observations provide an order-of-magnitude stronger constraint on the optical depth due to free–free absorption in the source's local environment. The absence of circular polarization and nearly flat polarization angle curves are consistent with burst properties seen at 300–1700 MHz. Compared with higher frequencies, the larger burst widths (∼40–160 ms at 150 MHz) and lower linear polarization fractions are likely due to scattering. We find ∼2–3 rad m−<sup>2</sup> variations in the Faraday rotation measure that may be correlated with the activity cycle of the source. We compare the LOFAR burst arrival times to those of 38 previously published and 22 newly detected burns from the uGMRT (200–450 MHz) and CHIME/ FRB (400–800 MHz). Simultaneous observations show five CHIME/FRB bursts when no emission is detected by LOFAR. We find that the burst activity is systematically delayed toward lower frequencies by about 3 days from 600 to 150 MHz. We discuss these results in the context of a model in which FRB 20180916B is an interacting binary system featuring a neutron star and high-mass stellar companion. Unified Astronomy Thesaurus concepts: Radio transient sources (2008); High energy astrophysics (739); Neutron stars (1108) 1. Introduction The discovery of radio pulsars (Hewish et al. 1968) using a lowfrequency dipole array (81.5 MHz) established the existence of neutron stars and demonstrated that short-duration, coherent radio events. The prediction of coherent radio bursts from other extreme astrophysical settings and events (e.g., Colgate & Noerdlinger (Thornton et al. 2013), in archival Parkes pulsar survey data led to the establishment of a population of fast radio bursts (FRBs). The FRBs are subsecond radio flashes that can be detected over extragalactic distances (see Cordes & Chatteries 2019 and Petroff et al. 2019 for recent reviews). Their physical origin is as yet unclear, but dozens of models have been proposed (see Platts et al. 2019, for a catalog<sup>33</sup> of theories). Both repeating (Spitler et al. 2016) and apparently nonrepeating (Petroff et al.

The Astrophysical Journal Letters, 911:L3 (18pp), 2021 April 10 https://doi.org/10.3847/2041-8213/abec722

Published papers

Press releases

<sup>23</sup> https://frbtheorycat.org/

2015; Shannon et al. 2018) FRBs have been detected and could

pulsar survey data (e.g., Phinney & Taylor 1979). The discovery of the "Lorimer Burst" (Lorimer et al. 2007), and other bursts with dispersion time delays that place them outside of our Galaxy

New scientific directions

New technical innovations



**Netherlands Institute for Radio Astronomy** 

# **Parameter space**



Shimwell

### **Observing capabilities Ultra-low radio frequencies**

Vedantham et al. 2020 Image credit: Daniëlle Futselaar

### **Observing capabilities**

**(sub-)arcsecond angular resolution**



Morabito + Surveys KSP

### **Observing capabilities High time resolution**

Pleunis et al. 2021

Image credit: Daniëlle Futselaar

**DSphere and Space OFAR 2.0.** 

a Morosan, Nataliya Porayko, Mario M. Bisi,<br>'ej Krankowski, Gottfried Mann, Jasmina arina Tiburzi, and Christian Vocks

acceleration of particles, the expulsion of plasma into the<br>Iy affecting the conditions of the ionosphere. However, the<br>Is in our understanding of the since to investigation. With the<br>space-based observing technology. By u

#### eliosphere

#### anetary Scintillation (IPS)

ation of a compact radio source due to density ns in the solar wind) is commonly used to observe the<br>ind throughout the inner heliosphere. The combination tu and remote sensing instrumentation available to ed over the next such observations is unprecede and must be taken full advantage of. Significan es in the analysis of IPS measu ents, playing to the strengths of LOFAR, have been made recently, paving ental understanding of the to a more funda ing solar wind turbulence, and how that may be ated with the large white light imag ing towards an exp ated with an evolution of the global solar wind s icreasing chances of CMEs. Taken tog ants an enormous opportunity to exploit the cap

AR2.0 in this arena



of the passage of a CME

Ir Dispersion Measure and Rotation Measure sion is modified by the action of the lasma, that can induce four kinds of r emis  $_{\text{etized}}$ tions can lead to the in field of the With LOFAR2.0 we and on the sously and with a to the ature thanks to the pot LBAs and HBAs simultan

**COFARED** Expression of Interest LOFAR2.0 Dark Matter eXperiment (LoDMaX) Aritra Basu<sup>1</sup> (abasu@tls-lautenburg.de), Dominik J. Schwarz<sup>1</sup> (de The nature of dark matter (DM) remains elusive, and various types of

matter including particles beyond the Standard Model and massive ob Jects have been put forward as its candidate. Although DM are not vis-The directly, depending on their nature, they can manitest through the Ture Unrocury, organisating our organisation, they can member include the<br>Tect processes or via the effects they have on electromagnetic radiation Many of these processes leave measurable imprints on astrophysical Many of a more processes heave included by the series of a series of a series of a series of a series of the SCRR C Can play a . The LODMaX large programme will systematically hunt for dark matter

. LODMaX will focus on detecting ultralight axion-like particles (ALPs) and **QCD** axions through signatures of birefringence, stimulated decay and axion-photon conversion, and decay products of annihilating weakly-interacting massive particles (WIMPs)

. LODMaX will also foster imaging-synergy with beamformer to search for exotic sterile neutrinos and primordial black holes . The parameter space that LODNaX will probe can not only compete with dedicated DM search experiments, but potentially improve the search dramatically.

andidates of dark man adapted from Bertone & Tai 2018. Nature 562 511 The shaded circles show the car idate space LoDMaX will ex plore. The dashed circles i MaX will coordinate with



The Diverse and three show the space sections will probe in search for unaign ALPs via.<br>"In the Diversity and the lens detected by the LOFAR2.0 can improve the exclusion"<br>"In the comparation and code of meaning the compara Left: The blue dashed lines show the space is the than an order of magnitude compared to deducted arion search sperm

In comparison, it will require observations of ~ 100 lenses by the VLA I space expected to be probed by LOFAR2.0 HBAs and LBAs (in gray) though of about 40 DM-rich systems to search for spectral line emission due to Ph will probe a complementary parameter space towards lower man The current and three ends of the based OCD axion searches and improved the current and future efforts of lab passed OCD axion searches and improved the current and through the current and through bounds by more than an order of magnitude.

ment direct WIMP sea

tax towards WIMP anni

Right:

· A tin on of Al Pe BS. ache ions, the Primakoff effect. I) due to ultra-light ALPs hakoff effect is expected to give rise to spectral-true

Jy/12.21 kHz near 140 MHz). systems, like, dwarf Spheroidals (dSph), elipt

ting massive particles (WIMPs) are being a

ral lab-based experiments, e.g., the XEND he CRESST and the FDFI WEIG natively, signatures of WIMPe.

hey annihilate via various channels pr pairs. So far, astrophysical searches have or

ses in the GeV-TeV range an

curb as dSphan ype ellipticals. A combination of LBA+HBA observations





LBA LOFAR Community Sky Survey

FAAC Relonization Survey (AF





**SALITTINIA** 





...some of the 20 Eol posters

### **LOFAR2.0 Science White Paper**







### LOFAR2.0 Large Programmes



LOFAR is the largest and most sensitive radio telescope operating at low radio frequencies, between 10 and 240 MHz. It consists of antenna stations geographically distributed across Europe and driven in software by powerful station-level computing to produce a highly flexible and agile observing system. With a sensitivity more than 2

Deadline: October 12th, 2023 at 12:00 UTC

### LOFAR2.0 Large Programmes

#### • **15 full proposals**

o From dozens of PIs and hundreds of co-Is, spanning the LOFAR partner countries

#### • **Diverse topics**

o Lightning, star-formation, SNRs, transients, cosmic rays, deep surveys, cosmology, galaxy clusters, Sun & heliosphere, exoplanets, pulsars & FRBs, magnetism

#### • **All together a (very) ambitious programme**

o Can only come to fruition by working together

Submission: LOFAR2.0 Large Programmes — Full proposal

#### **LOFAR2.0 Pulsar & Fast Transient Surveys**

Jason **Hessels<sup>1,2</sup>, Cees Bassa<sup>1</sup>, Maura Pilia<sup>3</sup>, Charlotte <b>Sobey<sup>4</sup>, Ben Stappers<sup>5</sup>,** Shivani Bhandari<sup>2,6</sup>, Leszek Blaszkiewicz<sup>7</sup>, Marta Burgay<sup>3</sup>, Manisha Caleb<sup>8</sup>, Jesus Alberto Cázares*<sup>9</sup>* , Pragya Chawla*<sup>2</sup>* , Alessandro Corongiu*<sup>3</sup>* , Marcin Gawronski*<sup>10</sup>*, Aaron Golden*<sup>11</sup>*, J.-M. Griessmeier*12,13*, Akshatha Gopinath*<sup>2</sup>* , Gemma Janssen*1,14*, Aris Karastergiou*<sup>15</sup>*, Evan Keane*<sup>16</sup>*, Mark Kennedy*<sup>17</sup>*, Franz Kirsten*<sup>18</sup>*, Vladislav Kondratiev*<sup>1</sup>* , Kamen Kozarev*<sup>19</sup>*, Michael Kramer*20,5*, David McKenna*21,16*, Daniele Michilli*22,23*, Leah Morabito*24,25*, Rouhin Nag*<sup>3</sup>* , Cherry Ng*<sup>26</sup>*, Kenzie Nimmo*<sup>22</sup>*, Aditya Parthasarathy*<sup>1</sup>* , Ziggy Pleunis*<sup>26</sup>*, Andrea Possenti*<sup>3</sup>* , Harry Qiu*<sup>27</sup>*, Kaustubh Rajwade*1,5*, Alesssandro Ridol*<sup>3</sup>* , Antonia Rowlinson*1,2*, Maciej Serylak*27,28*, Xiaoxi Song*<sup>1</sup>* , Laura Spitler*<sup>22</sup>*, Chia Min Tan*<sup>29</sup>*, Caterina Tiburzi*<sup>3</sup>* , Sander ter Veen*<sup>1</sup>* , Dany Vohl<sup>2,1</sup>, Jun Wang<sup>30</sup>, Emma van der Wateren<sup>1,14</sup>, Patrick Weltevrede<sup>5</sup> and Ziwei Wu*<sup>31</sup>*

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### Firehose rodeo with LOFAR2.0



#### Inspired by Daniela Huppenkothen



**Netherlands Institute for Radio Astronomy** 

### **LENSS - LOFAR Enhanced Network for Sharp Surveys**

- Community consultations in NL and with LOFAR partners
- Where can we have a large and unique impact in the coming decade?
- 2024: NWO-RI for upgraded network (10→100Gb/s) and full-FoV, full-res imaging
- 2026: NWO-Roadmap focusing on ultra-low frequencies?





### LOFAR2.0 Large Programmes

### **Success Criteria**

### • **Scientific impact**

o Publications, citations, theses, prizes, grants

• **Technical impact**

o Techniques, software

• **Community impact**

o Partner countries & institutes, support ECRs, develop SKA leadership roles

• **Accessibility & legacy**

oData reuse, distilled data products

#### • **Visibility**

o Make LOFAR better known to other astronomers, policy makers, the public



### LOFAR2.0 Commissioning



Hardware Science ideas Software Algorithms Expertise Computing





Published papers New scientific directions Press releases New technical innovations



## **Impact of LOFAR2.0**







**Major new suite of science at a fraction of the original investment in LOFAR**