

# **Capitalizing on wearable sensors and smartphones to robustly assess longitudinal symptom severity trajectories**

**Application in mental disorders, post-traumatic  
stress disorder, and stroke**

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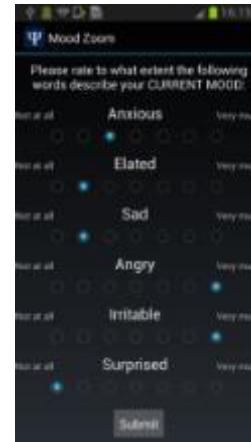
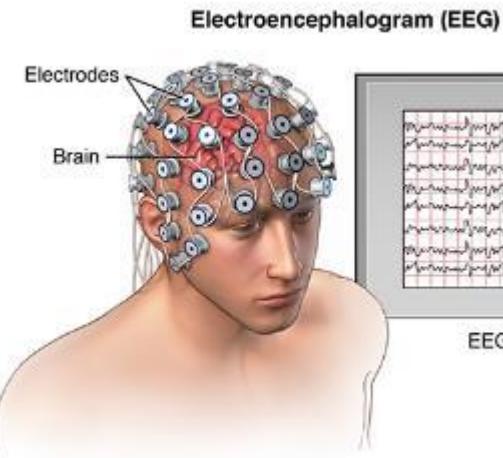


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**U**usher  
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# Research vision

## Address unmet clinical needs

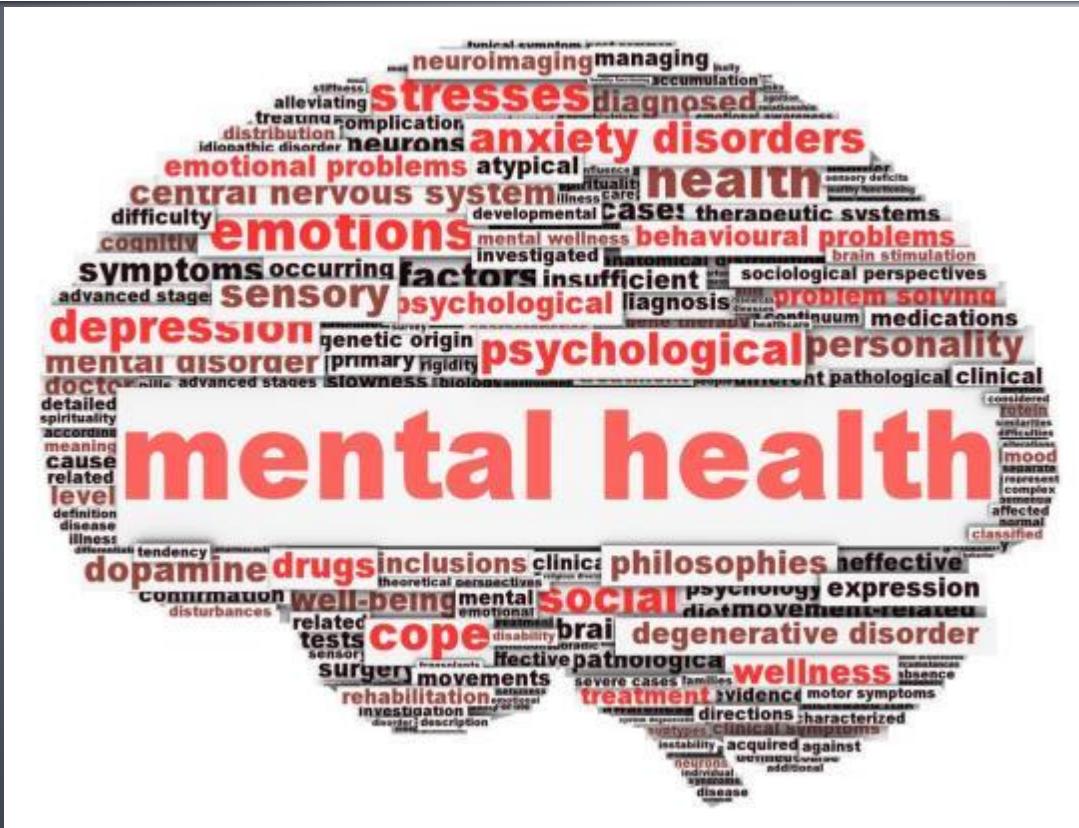


## Assessment & Monitoring

- Frequent
- Unobtrusive
- Personalised
- Inexpensive
- Massive scale

# Mental health telemonitoring (AMoSS project)

## Project 1



Oxford Health **NHS**  
NHS Foundation Trust

# Problem with current assessment



## Physical presence in the clinic

- Cumbersome for those living in remote areas
- People need to take days off work

## Patient-led self-monitoring

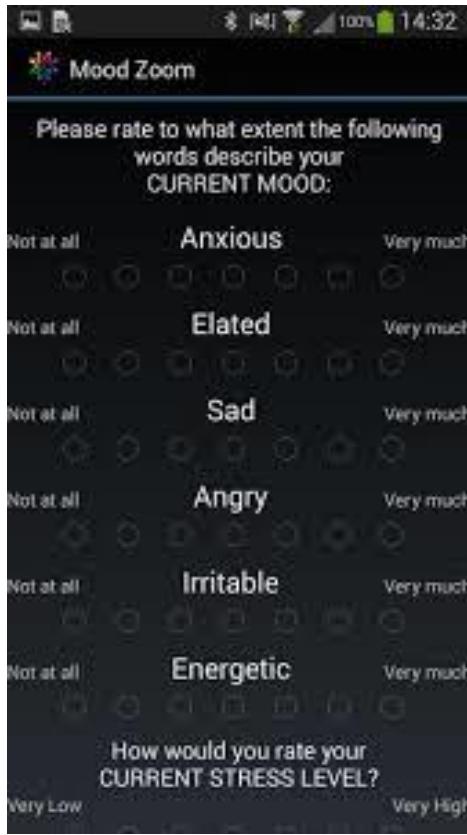
- 
- A photograph showing a patient's hand holding a pen over a piece of paper titled "QUESTIONNAIRE". The paper lists response options: "Very often", "Often", "Sometimes", and "Rarely", each next to a small square checkbox. Some checkboxes are marked with a checkmark.
- Recall bias
  - Subjectivity

## No ground truth

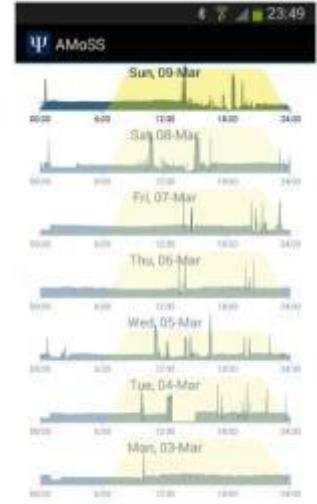
- 
- A photograph of a doctor in a white coat and a patient sitting at a table, both looking down at something on the table, possibly a tablet or a document.
- Difficult to objectively assess intervention effects
  - Inter-rater variability

# Proposed solution

- Frequent time-stamped self-reports
- Sensor-based objective monitoring



# Assessing mental health



- Continuous personalized monitoring
- Objectively quantify mental health
- Identify characteristic patterns

A screenshot of the Mood Zoom mobile application. It asks the user to rate words describing their current mood on a scale from 'Not at all' to 'Very much'. The words are: Anxious, Elated, Sad, Angry, Irritable, and Surprised. Below the scale are small circular icons for each word. At the bottom is a 'Submit' button.

## Quick Inventory of Depressive Symptomatology—Self-Report (QIDS-SR)

Please check the one response to each item that best describes you for the past seven days.

1. Depressed:
  1. I feel down, blue, or hopeless more than half the time.
  2. I feel irritable and restless more than half the time.
  3. I feel unmotivated or have no energy more than half the time.
2. Sleep disturbance:
  1. I have trouble falling asleep.
  2. I wake up during the night with a few thoughts each night.
  3. I wake up too early and can't get back to sleep easily.
3. Weight gain/loss:
  1. I eat more than usual because I feel like I need to.
  2. More than half the time, I eat more than 20% more than I normally do.
  3. I feel full after eating less than one hour before I feel I need to eat again.
4. Slowing down:
  1. I feel slow, tired, or sluggish more than half the time.
  2. I take longer than 20% longer to do things.
  3. I take longer than 20% longer to do things, which may be normal.
  4. I feel along the 12 hours of the day, 20% longer walking, talking, etc.
5. Fidgety:
  1. I feel fidgety or wound up.
  2. I feel nervous or jumpy more than half the time.
  3. I feel jittery or wound up most of the time.
6. Distressed appetite:
  1. I have a change in my appetite.
  2. I feel more hungry than usual.
  3. I eat more than usual, but don't feel pleasure from it.
  4. I feel full after eating 20% more than usual, but still want to eat.

# AMoSS project data



- 48 Bipolar Disorder (BD)
  - 31 Borderline Personality Disorder (BPD)
  - 51 Healthy Controls (HC)
- 
- ❖ Questionnaires: ASRM, QIDS, GAD-7 + MZ (novel)
  - ❖ Data collected over a year for most participants

# Self-assessment: questionnaires



Welcome

Welcome to the  
Mood Zoom Demo App

UNIVERSITY OF OXFORD

We will now take a few moments to set up  
the app with you

Begin

The app interface includes a navigation bar at the top with icons for file operations (New, Open, Save, etc.) and a battery level indicator. Below the navigation bar, the title "Welcome" is displayed above a large, dark background area. In the center of this area, the text "Welcome to the Mood Zoom Demo App" is displayed in a white sans-serif font. To the right of the text is the circular "UNIVERSITY OF OXFORD" crest. At the bottom of the screen, a large, semi-transparent button with the word "Begin" in white is centered. On the left side of the screen, there is a vertical list of mood-related words: "Anxious", "Elated", "Sad", "Angry", "Irritable", and "Energetic". Each word is accompanied by a horizontal scale from "Not at all" on the left to "Very much" on the right, with five intermediate points labeled "A little", "Somewhat", "Moderately", "Quite a bit", and "Extremely". At the very bottom of the screen, there is another section titled "How would you rate your CURRENT STRESS LEVEL?" with a similar rating scale from "Very Low" to "Very High".

## Quick Inventory of Depressive Symptomatology—Self-Report (QIDS-SR)

Please circle the one response to each item that best describes you for the past seven days.

1. Falling asleep:

- 0 I never take longer than 30 minutes to fall asleep.
- 1 I take at least 30 minutes to fall asleep, less than half the time.
- 2 I take at least 30 minutes to fall asleep, more than half the time.
- 3 I take more than 60 minutes to fall asleep, more than half the time.

2. Sleep during the night:

- 0 I do not wake up at night.
- 1 I have a restless, light sleep with a few brief awakenings each night.
- 2 I wake up at least once a night, but I go back to sleep easily.
- 3 I awaken more than once a night and stay awake for 20 minutes or more, more than half the time.

3. Waking up too early:

- 0 Most of the time, I awaken no more than 30 minutes before I need to get up.
- 1 More than half the time, I awaken more than 30 minutes before I need to get up.
- 2 I almost always awaken at least one hour or so before I need to, but I go back to sleep eventually.
- 3 I awaken at least one hour before I need to, and can't go back to sleep.

4. Sleeping too much:

- 0 I sleep no longer than 7–8 hours/night, without napping during the day.
- 1 I sleep no longer than 10 hours in a 24-hour period including naps.
- 2 I sleep no longer than 12 hours in a 24-hour period including naps.
- 3 I sleep longer than 12 hours in a 24-hour period including naps.

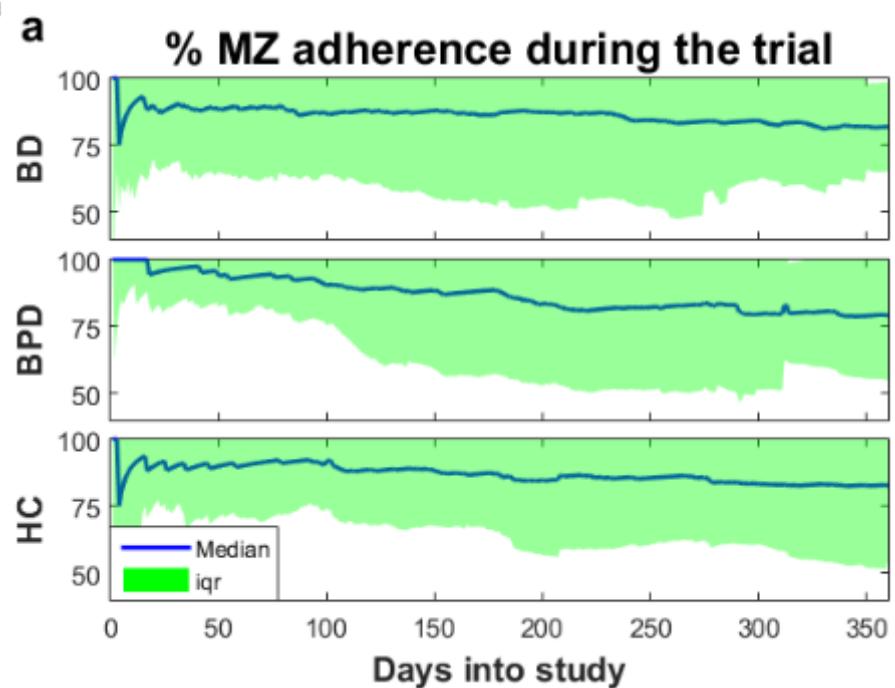
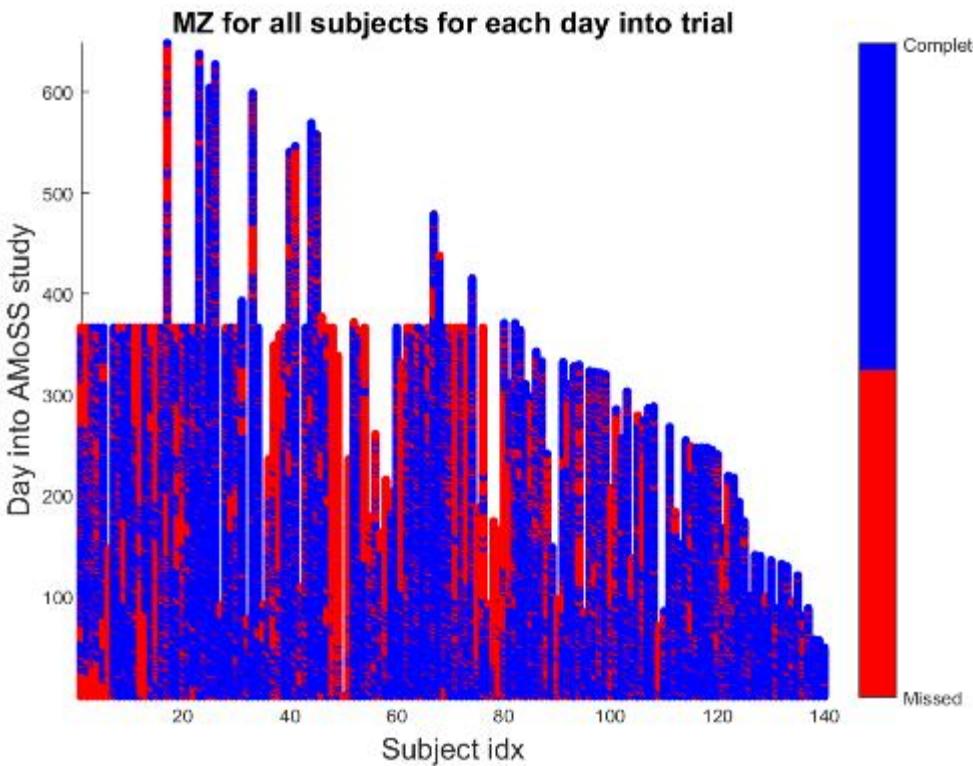
5. Feeling sad:

- 0 I do not feel sad.
- 1 I feel sad less than half the time.
- 2 I feel sad more than half the time.
- 3 I feel sad nearly all of the time.

6. Decreased appetite:

- 0 There is no change in my usual appetite.
- 1 I eat somewhat less often or lesser amounts of food than usual.
- 2 I eat much less than usual and only with personal effort.
- 3 I rarely eat within a 24-hour period, and only with extreme personal effort or when others persuade me to eat.

# AMoSS adherence >80%

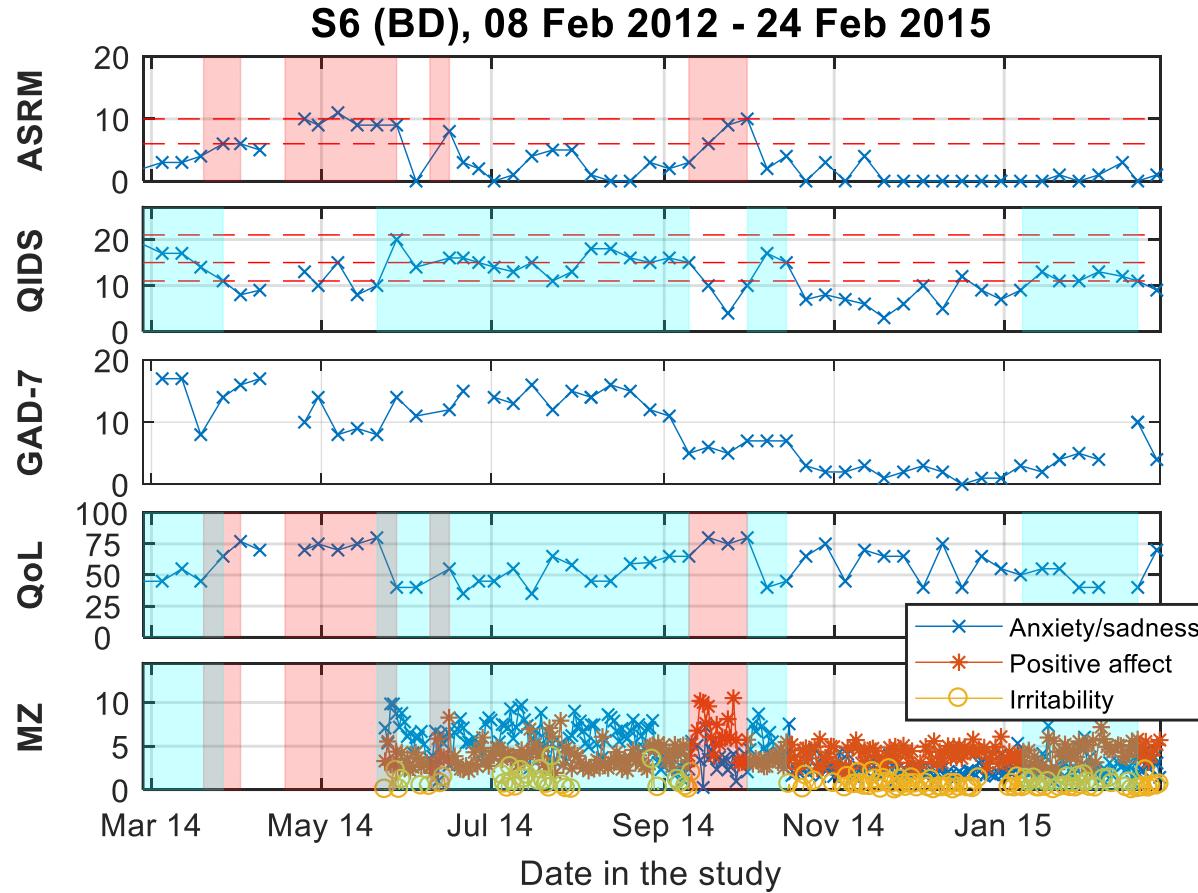


- Longitudinal, daily monitoring of mood

# Interpretable clinical latent variables

	P1	P2	P3	P4	P5	P6
Anxious	<b>0.55</b>	0.08	<b>-0.47</b>	-0.27	0.60	0.18
Elated	-0.11	<b>0.76</b>	-0.11	-0.53	-0.33	0.01
Sad	<b>0.52</b>	0.04	<b>-0.43</b>	0.39	-0.57	-0.25
Angry	<b>0.42</b>	0.11	<b>0.46</b>	0.11	-0.21	0.74
Irritable	<b>0.47</b>	0.12	<b>0.60</b>	-0.15	0.14	-0.60
Energetic	-0.13	<b>0.62</b>	0.020	0.67	0.38	-0.03
% Total variance explained	55	77	85	91	97	100
Tentative interpretation	“Negative feelings”	“Positive feelings”	“Irritability”			

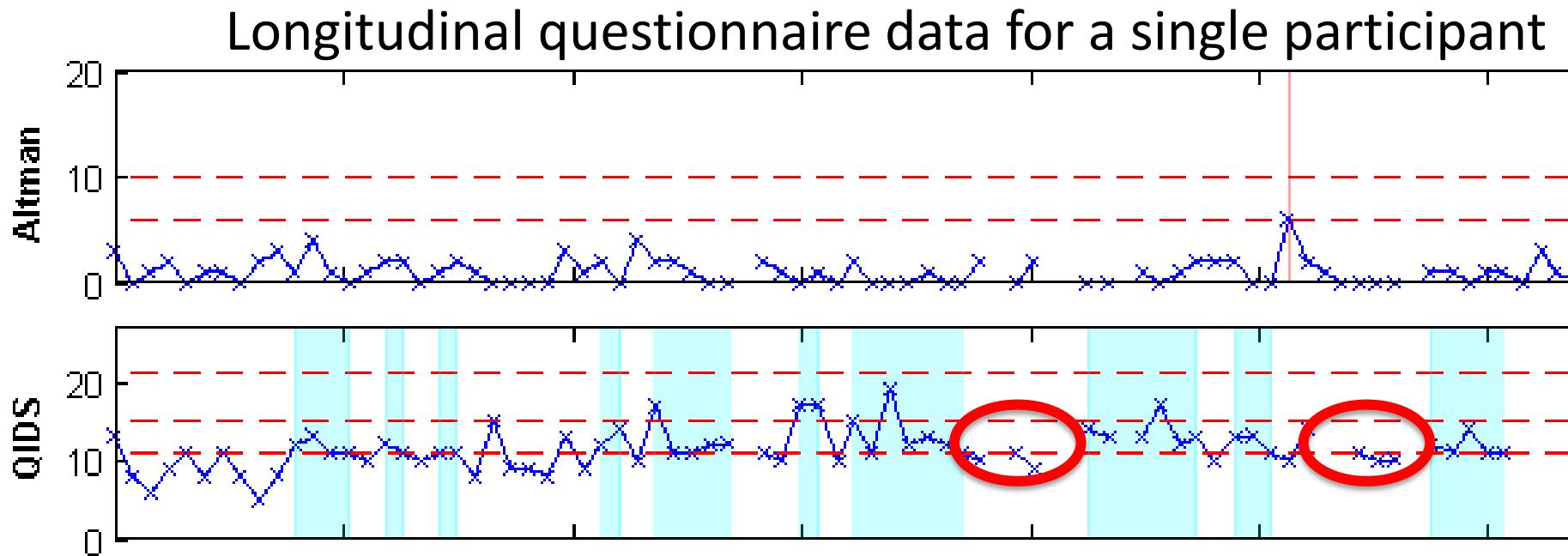
# Self-assessment: questionnaires



A. Tsanas et al.: Daily longitudinal self-monitoring of mood variability in bipolar disorder and borderline personality disorder, **Journal of Affective Disorders**, Vol. 205, pp. 225-233, 2016

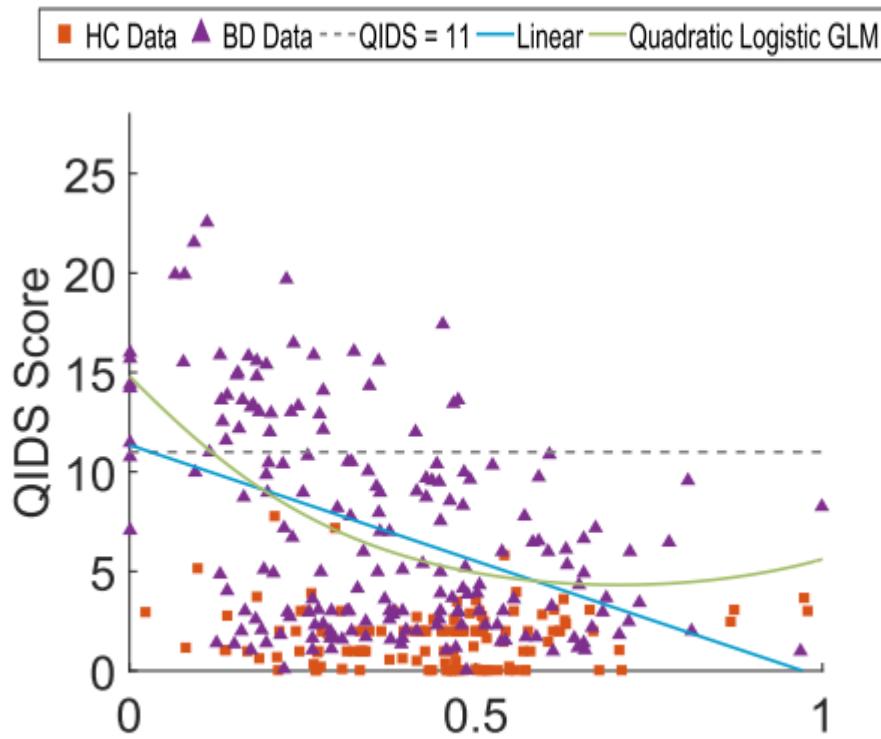
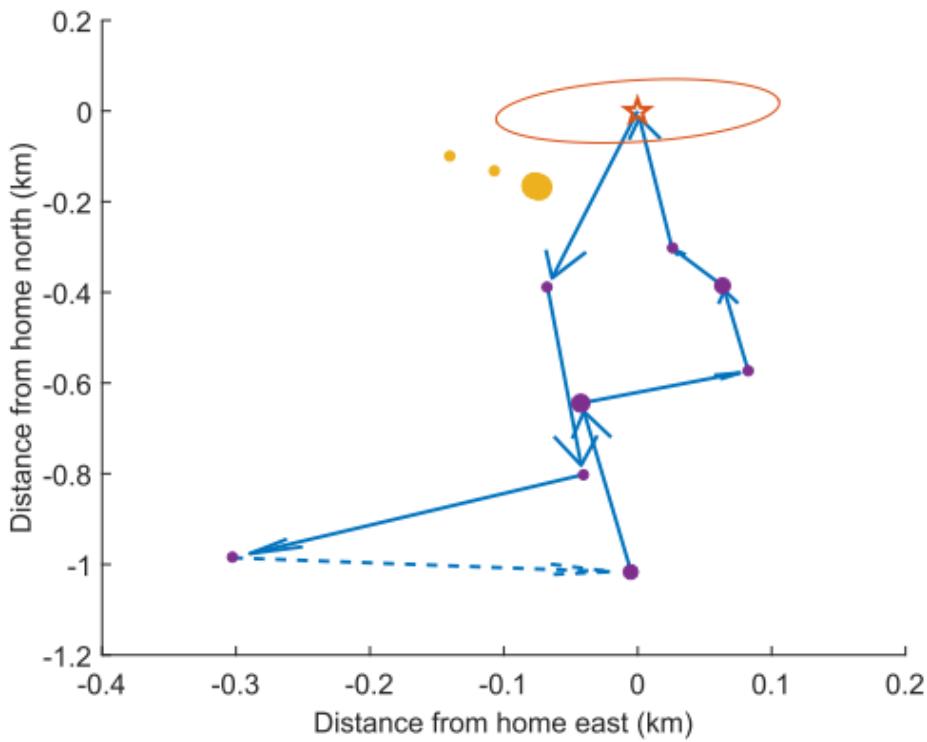
A. Tsanas et al.: Clinical insight into latent variables of psychiatric questionnaires for mood symptom self-assessment, **JMIR Mental Health**, Vol. 4, pp. e15, 2017

# Missing data (example)



- Potentially conveys information
- Identify patterns of missing data and scores

# Geolocation and depression



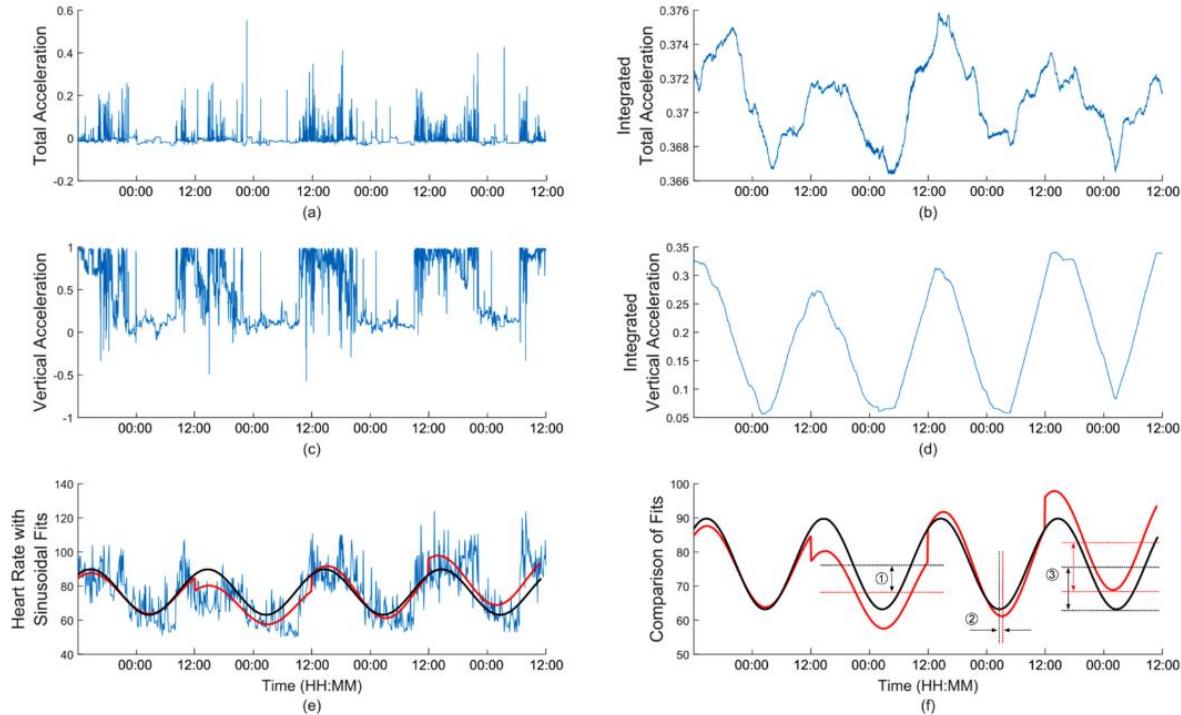
N. Palmius, A. Tsanas, K.E.A. Saunders, A.C. Bilderbeck, J.R. Geddes, G.M. Goodwin, M. De Vos:  
Detecting bipolar depression from geographic location data, **IEEE Transactions on Biomedical Engineering**, Vol. 64, pp. 1761-1771, 2017

# Circadian variability and mood in mental disorders



- **AMoSS-Proteus dataset**

- “High intensity” monitoring
- Mapping circadian variability to mood



- O. Carr, K.E.A. Saunders, A.C. Bilderbeck, A. Tsanas, N. Palmius, J.R. Geddes, R. Foster, M. De Vos, G.M. Goodwin: Desynchronization of diurnal rhythms in bipolar disorder and borderline personality disorder, **Translational Psychiatry**, Vol. 8:79, 2018
- O. Carr, K.E.A. Saunders, A. Tsanas, A.C. Bilderbeck, N. Palmius, J.R. Geddes, R. Foster, G.M. Goodwin, M. De Vos: Variability in different diurnal rhythms is related to variation of mood in bipolar and borderline personality disorder, **Scientific Reports**, Vol. 8:1649, 2018

# Smartwatch processing



RAM Offset 0x000107	
marks	Help
8 00	B3 11 81 84 19 84 00 00 42 F6 FF 0C :
7 00	00 42 00 00 04 00 00 66 00 00 2C 00 :
0 2C	48 07 00 00 00 00 00 00 BA E0 00 :
2 9F	D8 A4 18 B4 03 00 00 00 00 00 00 00 00 :
0 00	00 FF FF FF FF FF 00 00 00 00 00 00 00 :
0 09	00 30 00 00 00 02 00 F8 00 00 00 00 00 :
0 00	00 02 9C 2F 00 00 FF E0 00 38 03 00 :
0 1A	02 00 00 01 21 2A 00 00 A8 40 00 00 :
2 A8	00 00 00 01 04 0E 00 D0 00 02 00 01 :
0 21	00 00 00 80 00 00 00 00 FF 00 00 00 00 :
2 00	C0 00 00 00 00 00 00 00 00 00 00 00 00 00 :
2 00	05 00 00 00 00 02 00 00 00 00 00 00 00 00 :
1 01	00 00 FF FF 00 00 00 01 18 00 9E F0 >x:
0 00	00 00 00 00 00 01 00 00 00 00 00 00 00 00 :
0 8C	25 3D EB 96 AD 8D FF 00 BA 04 00 00 F :

Raw data

Day	Time	Activity	Intensity
Tue, 19 Jul	08:00	Walking	Low
Wed, 20 Jul	08:00	Walking	Low
Thu, 21 Jul	08:00	Walking	Low
Fri, 22 Jul	08:00	Walking	Low
Sat, 23 Jul	08:00	Walking	Low
Sun, 24 Jul	08:00	Walking	Low
Mon, 25 Jul	08:00	Walking	Low
Tue, 26 Jul	08:00	Walking	Low
Wed, 27 Jul	08:00	Walking	Low
Thu, 28 Jul	08:00	Walking	Low
Fri, 29 Jul	08:00	Walking	Low
Sat, 30 Jul	08:00	Walking	Low
Sun, 31 Jul	08:00	Walking	Low
Mon, 1 Aug	08:00	Walking	Low
Tue, 2 Aug	08:00	Walking	Low
Wed, 3 Aug	08:00	Walking	Low
Thu, 4 Aug	08:00	Walking	Low
Fri, 5 Aug	08:00	Walking	Low
Sat, 6 Aug	08:00	Walking	Low
Sun, 7 Aug	08:00	Walking	Low
Mon, 8 Aug	08:00	Walking	Low
Tue, 9 Aug	08:00	Walking	Low
Wed, 10 Aug	08:00	Walking	Low
Thu, 11 Aug	08:00	Walking	Low

Processed patterns

Subjects	feature1	feature2	...	featureN
	3.1	1.3		0.9
	3.7	1.0		1.2
	2.9	2.6		0.6
	1.7	2.0		0.7

Features

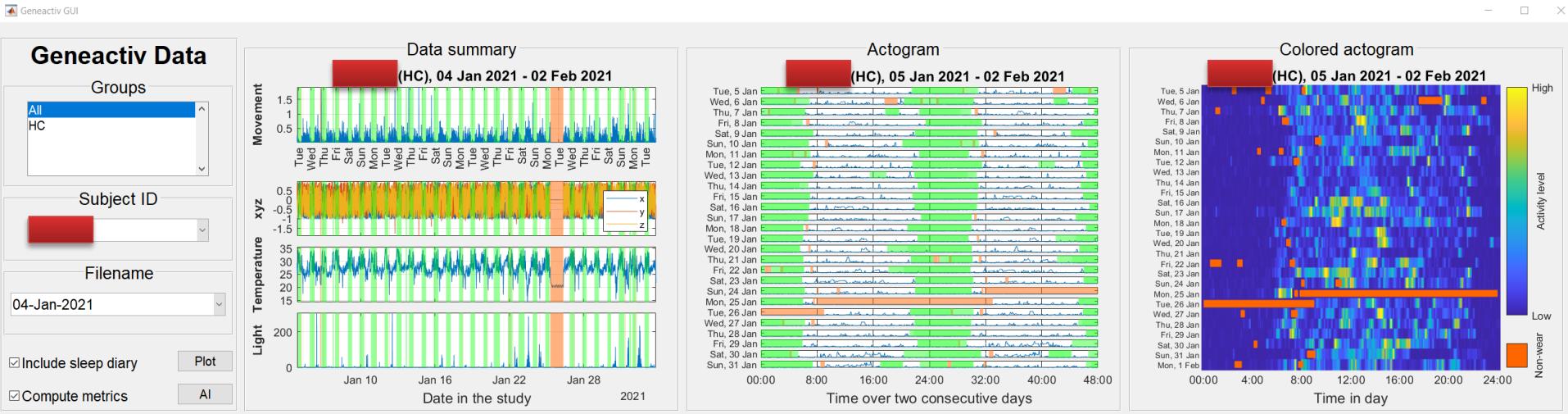
Extract data

Pre-process

Characterise

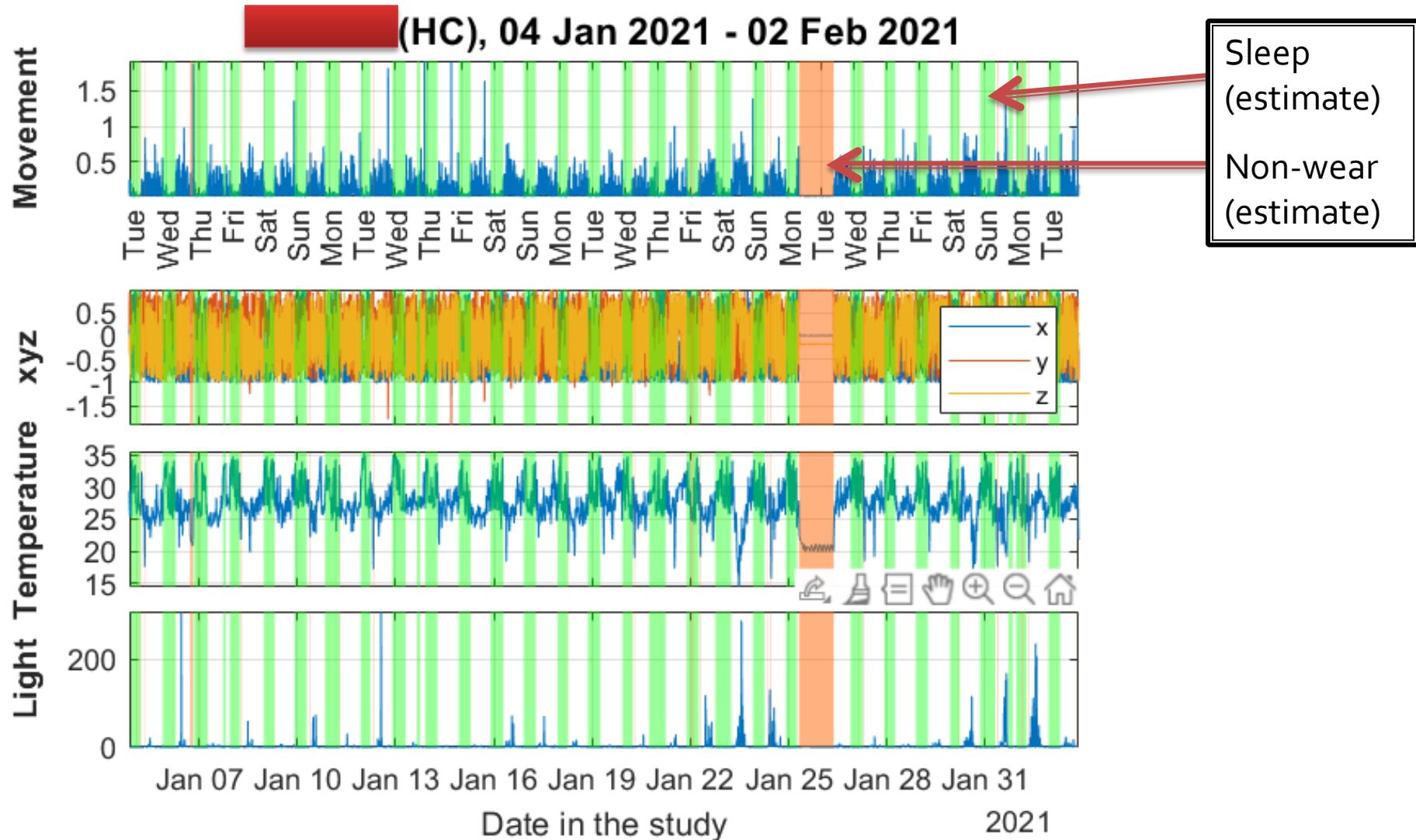
# Visualize multimodal data

- Database with all participants
- (used to blank out participant id)

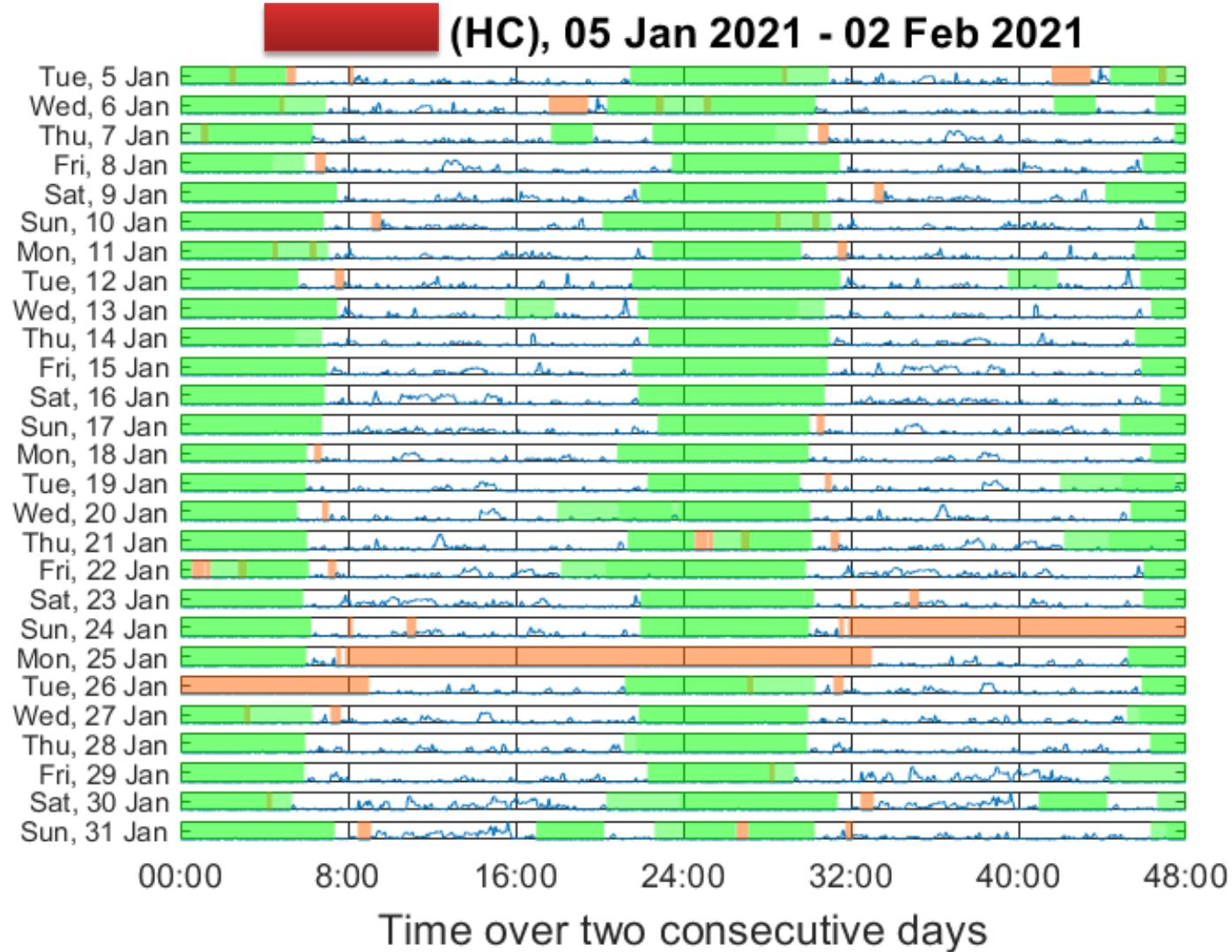


	05 Jan	06 Jan	07 Jan	08 Jan	09 Jan	10 Jan	11 Jan	12 Jan	13 Jan	14 Jan	15 Jan	16 Jan	17 Jan	18 Jan	19 Jan	20 Jan	21 Jan	22 Jan	23 Jan	24 Jan	25 Jan	26 Jan	27 Jan	28 Jan	29 Jan	30 Jan	31 Jan
M10	0.10	0.13	0.09	0.13	0.12	0.12	0.11	0.09	0.09	0.09	0.12	0.18	0.13	0.12	0.10	0.13	0.10	0.14	0.21	0.10	0.04	0.09	0.12	0.10	0.09	0.23	0.20
M10 time	07:40	07:06	06:18	06:57	11:54	09:35	07:52	11:10	07:22	07:03	07:17	06:51	07:55	10:19	05:57	23:31	06:12	08:11	07:38	09:57	00:12	11:56	06:51	11:04	12:20	08:29	07:00
L5	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	
L5 time	00:21	00:39	00:32	00:12	00:33	01:11	01:33	00:24	02:27	00:03	00:07	00:08	00:01	00:23	00:10	00:12	00:13	00:38	00:13	00:01	11:45	03:45	00:01	00:02	00:22	00:17	00:11
RA	0.68	0.75	0.64	0.74	0.72	0.72	0.71	0.66	0.62	0.63	0.74	0.81	0.73	0.74	0.68	0.73	0.69	0.76	0.82	0.68	0.38	0.67	0.70	0.66	0.64	0.84	0.81
IS1	0.40	0.44	0.45	0.53	0.50	0.45	0.50	0.29	0.33	0.31	0.52	0.66	0.55	0.52	0.74	0.52	0.50	0.63	0.64	0.44	0.83	0.43	0.50	0.35	0.43	0.64	0.74
IS2	0.37	0.46	0.41	0.64	0.44	0.50	0.51	0.31	0.35	0.33	0.53	0.69	0.57	0.61	0.61	0.54	0.43	0.62	0.64	0.50	0.81	0.44	0.45	0.37	0.40	0.64	0.71
IV1	1.11	1.31	1.67	0.87	1.35	0.75	0.94	0.75	1.59	1.11	0.54	0.52	0.93	1.89	1.54	1.46	0.95	0.75	0.89	1.47	0.86	1.61	1.42	1.40	0.53	0.53	
IV2	0.08	0.06	0.08	0.03	0.07	0.05	0.06	0.09	0.10	0.08	0.05	0.02	0.06	0.04	0.04	0.04	0.03	0.04	0.05	0.07	0.05	0.04	0.07	0.07	0.03	0.03	
IV3	0.44	0.56	0.54	0.43	0.42	0.39	0.37	0.42	0.72	0.61	0.50	0.27	0.23	0.45	0.58	0.57	0.54	0.40	0.27	0.47	0.13	0.32	0.60	0.68	0.61	0.17	0.17
MDA	0.08	0.12	0.08	0.10	0.10	0.10	0.10	0.09	0.09	0.08	0.11	0.15	0.11	0.10	0.08	0.09	0.09	0.13	0.15	0.08	NaN	NaN	0.10	0.09	0.08	0.18	0.14
MNA	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.04	0.02	0.03	0.02	0.02	NaN	0.03	0.02	0.02	0.02	0.03
MA	0.06	0.08	0.05	0.07	0.07	0.07	0.06	0.07	0.06	0.06	0.08	0.10	0.07	0.08	0.06	0.07	0.06	0.09	0.09	0.06	NaN	NaN	0.07	0.07	0.06	0.13	0.09
TD-COV	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	NaN	NaN	0.00	0.01	0.01	0.01	0.01
%NA	0.07	0.15	0.11	0.09	0.09	0.12	0.13	0.10	0.14	0.11	0.07	0.10	0.11	0.10	0.12	0.09	0.22	0.07	0.19	0.24	0.14	NaN	0.13	0.12	0.06	0.06	0.14
diurnal skewness	2.73	3.00	3.85	2.97	2.26	4.98	3.59	4.39	5.41	2.11	4.44	2.68	4.35	3.90	3.44	4.91	3.52	2.84	4.88	1.23	1.80	NaN	2.77	5.07	2.69	1.94	5.00

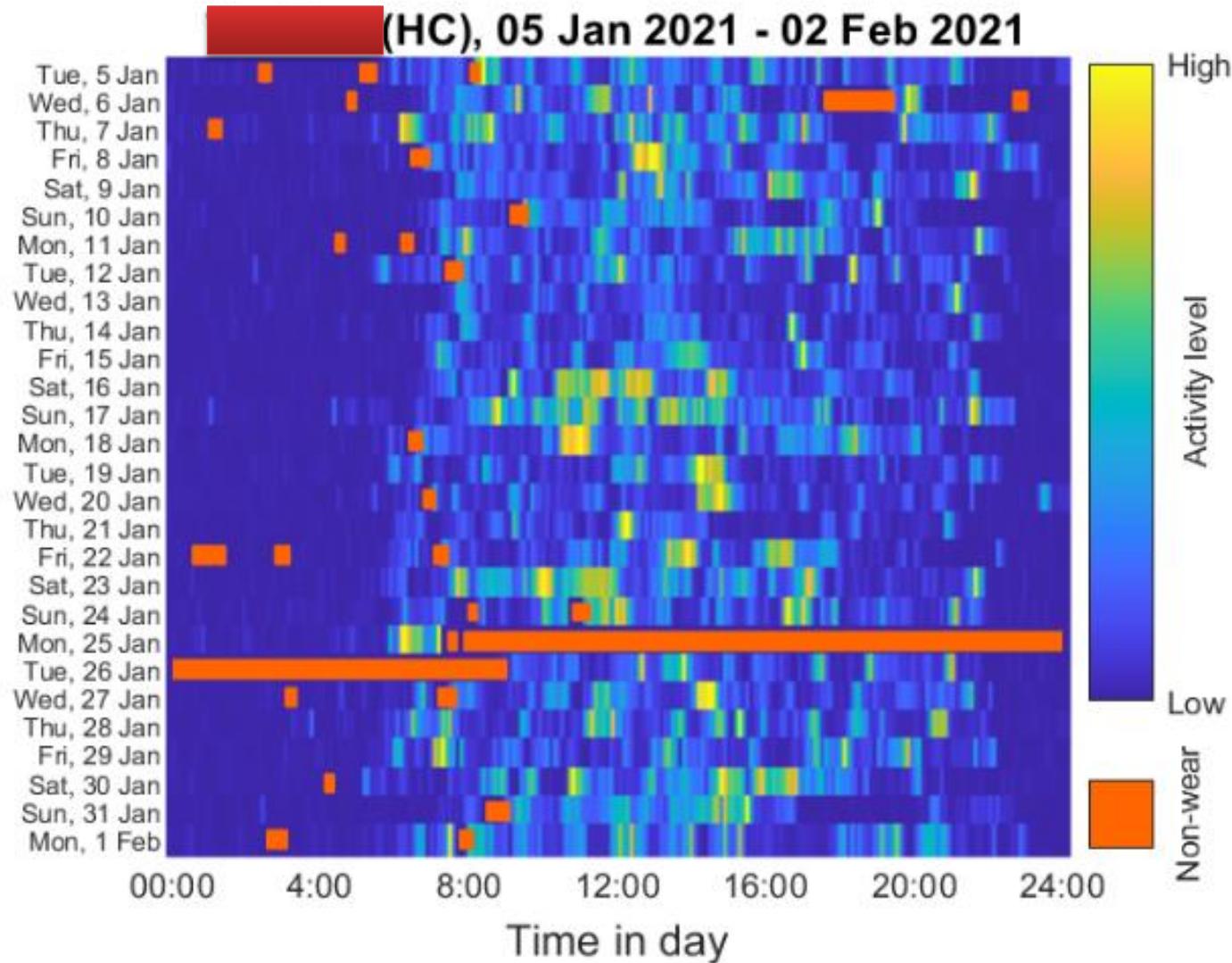
# Summary of data modalities



# Actogram



# Colored actogram



# Objective signal monitoring



Actogram: 14004 (HC), 01-Feb-2014 - 14-Feb-2014



Feature	Subject id
IS	$0.66 \pm 0.07$
IV	$0.01 \pm 0.00$
L5	$0.00 \pm 0.00$
M10	$0.16 \pm 0.01$
RA	$0.95 \pm 0.02$

(results in form: median±iqr)

IS = interdaily stability  
 IV = intradaily variability  
 RA = relative amplitude =  $(M_{10} - L_5) / (M_{10} + L_5)$

High IS: good zeitgeber sync ☺  
 High IV: fragmentation ☹  
 High RA: good rhythmicity ☺



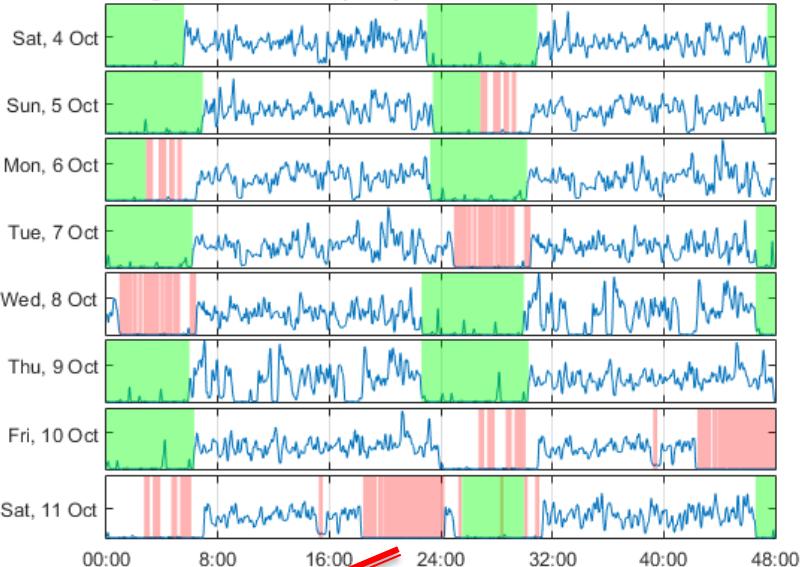
# Actograms + Questionnaires



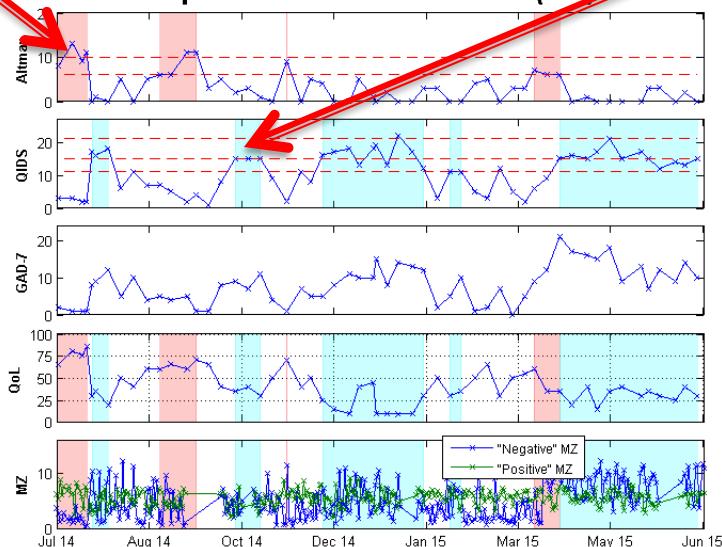
Actogram: 14047 (BD), 04-Jul-2014 - 10-Jul-2014



Actogram: 14047 (BD), 04-Oct-2014 - 12-Oct-2014



Episode assessment: 14047 (BD)



Feature	14047
IS	$0.65 \pm 0.09$
IV	$0.01 \pm 0.00$
L5	$0.00 \pm 0.00$
M10	$0.17 \pm 0.00$
RA	$0.95 \pm 0.04$

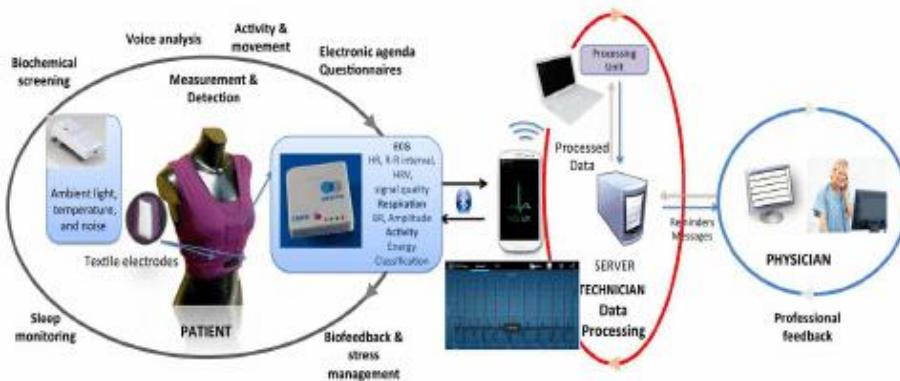
median  $\pm$  iqr

Feature	14047
IS	$0.72 \pm 0.08$
IV	$0.01 \pm 0.00$
L5	$0.00 \pm 0.00$
M10	$0.17 \pm 0.02$
RA	$0.97 \pm 0.03$

median  $\pm$  iqr

# Looking at colleagues' work...

## ■ Psyche system (t-shirt based)



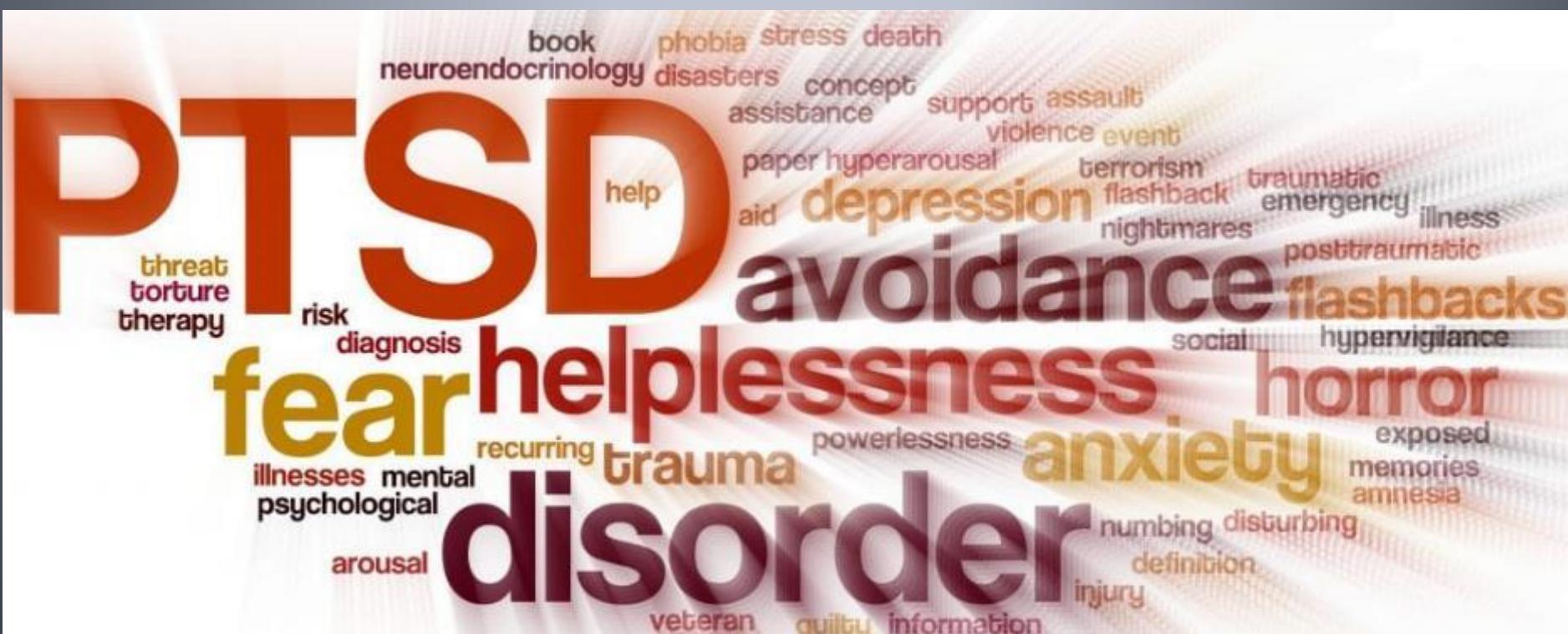
Valenza et al. *Wearable monitoring for mood recognition in bipolar disorder based on history dependent long-term heart rate variability analysis*, **IEEE Journal of Biomedical and Health Informatics**, Vol. 18, pp. 1625-1635, 2014

## ■ Lifelogging (cameras)



# PTSD objective treatment assessment using a smartwatch

Project 2



# Problem with current assessment



## Physical presence in the clinic

- Cumbersome for those living in remote areas
- People need to take days off work



## Patient-led self-monitoring

- Recall bias
- Subjectivity



## No ground truth

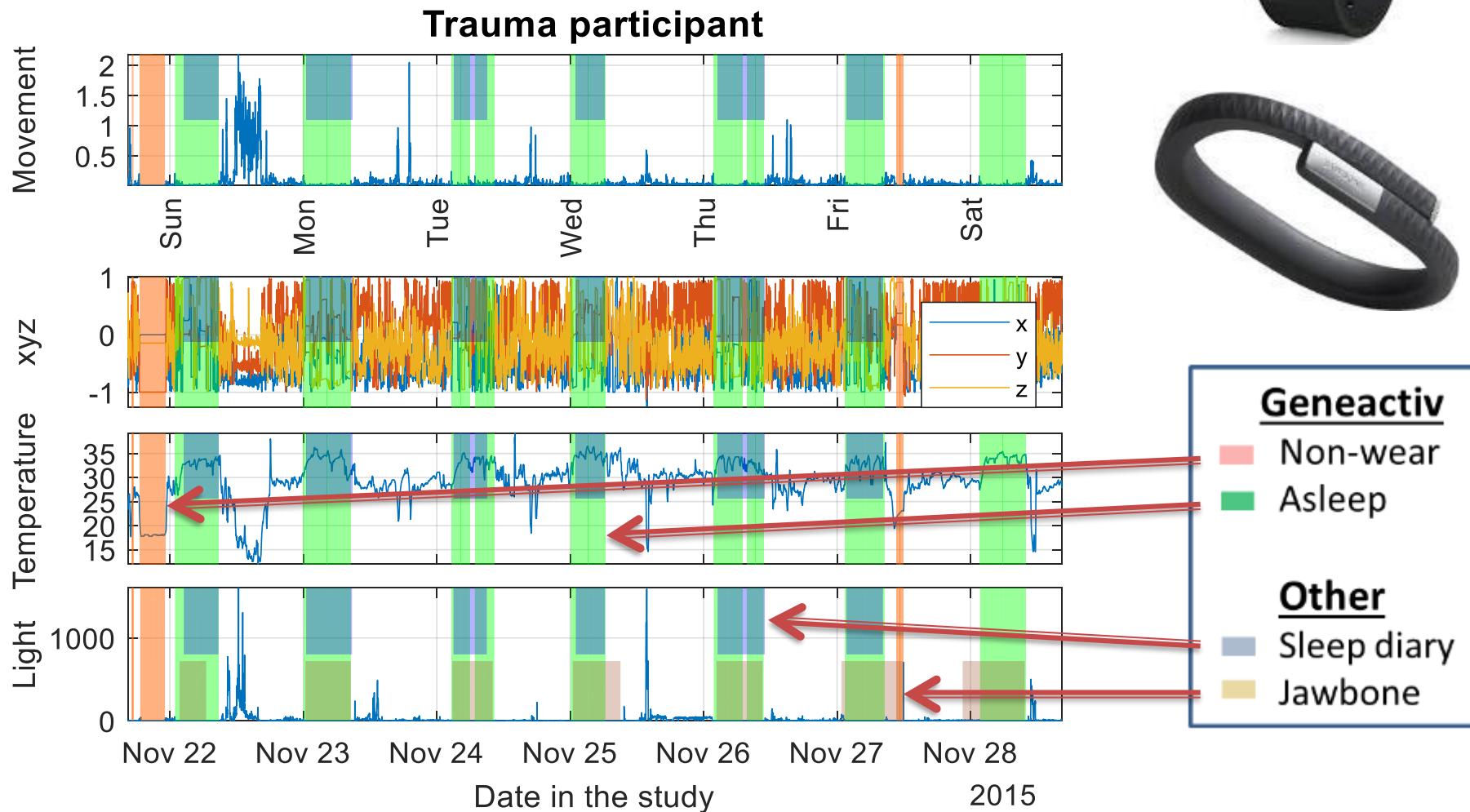
- Difficult to objectively assess intervention effects
- Inter-rater variability

# PTSD project data



- 42 PTSD participants
  - 43 traumatized controls
  - 51 Healthy Controls (HC)
- 
- ❖ Smartwatch (~1month)
  - ❖ Sleep diaries + PSQI
  - ❖ Collected before + after treatment

# Sleep detection example



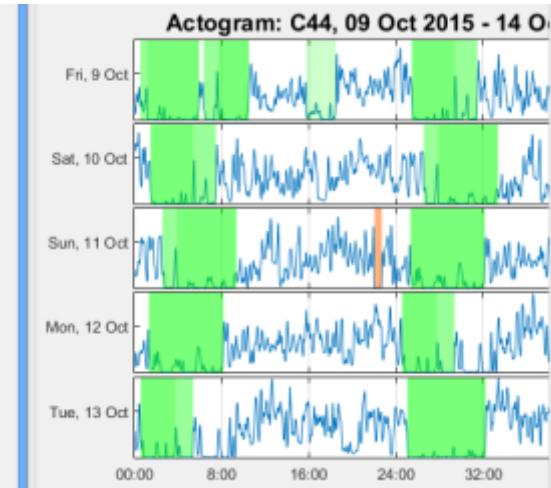
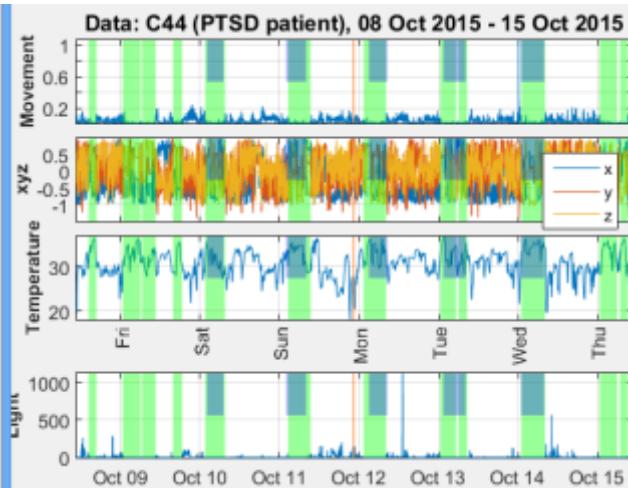
# Sleep detection comparisons

		van Hees et al. (2015) sleep detection algorithm		Proposed sleep detection algorithm in this study	
		Sleep onset	Sleep offset	Sleep onset	Sleep offset
Deviation from grand truth (minutes)	Non-traumatised controls	-56±112	22.5±106	-12.5±51	2±30.25
	Traumatised controls	-81±147	35.5±95.5	-18±50	10±46.75
	PTSD participants	-78±131.25	41.5±122.5	-34±78.25	10±45.25

A. Tsanas, E. Woodward, A. Ehlers: *Objective characterization of activity, sleep, and circadian rhythm patterns using a wrist-worn sensor: insights into post-traumatic stress disorder*, JMIR mHealth and uHealth, Vol. 8(5), e16452, 2020

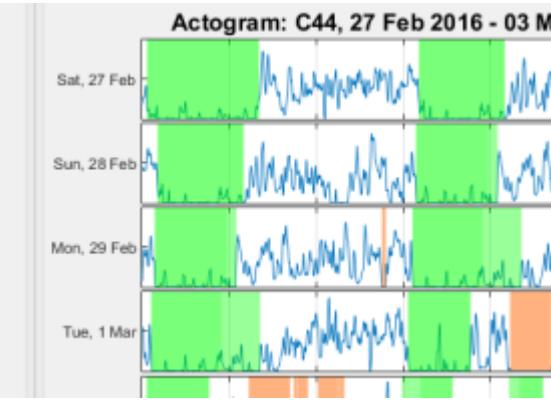
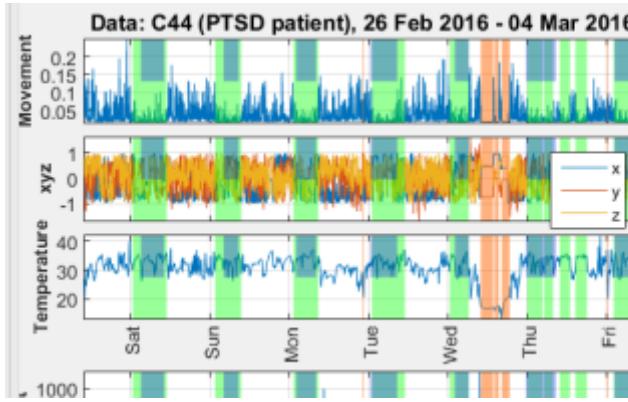
# PTSD, before and after treatment

**BEFORE**



	09 Oct	10 Oct	11 Oct	12 Oct
M10	0.15	0.16	0.14	0.15
L5	0.01	0.01	0.01	0.02
RA	0.86	0.86	0.89	0.80
IS	0.62	0.59	0.58	0.65
IV	0.02	0.02	0.02	0.02
mean activity	5.54	10.01	8.27	9.75
sleep onset	01:27	02:32	01:19	00:33
sleep offset	07:28	09:21	08:08	05:22
sleep duration	06:01	06:49	06:49	04:48
sleep onset phase	57.00	65.00	-73.00	-46.00
sleep offset phase	93.00	113.00	-73.00	-166.00
sleep_activity 1%	0.73	0.97	0.97	1.10
sleep_activity 5%	1.57	1.57	1.31	1.31
sleep_activity 10%	2.27	2.01	1.58	1.44
sleep_entropy	3.01	3.19	2.92	3.05
sleep temp zenith	35.50	35.42	36.34	36.70
sleep temp zenith time	01:55	03:49	07:17	01:42

**AFTER**



	27 Feb	28 Feb	29 Feb	01 Mar
M10	0.17	0.13	0.15	0.19
L5	0.01	0.00	0.01	0.01
RA	0.92	0.94	0.87	0.91
IS	0.76	0.69	0.61	0.76
IV	0.01	0.01	0.01	0.01
mean activity	9.42	6.51	8.36	7.95
sleep onset	01:24	01:08	00:49	00:24
sleep offset	09:18	08:38	10:50	06:09
sleep duration	07:54	07:30	10:00	05:44
sleep onset phase	58.00	-16.00	-19.00	-25.00
sleep offset phase	-86.00	-40.00	132.00	-281.00
sleep_activity 1%	1.50	1.44	0.92	1.75
sleep_activity 5%	1.85	1.87	1.48	2.17
sleep_activity 10%	3.15	2.51	1.74	3.51

# Stroke objective assessment using a smartwatch

Project 3



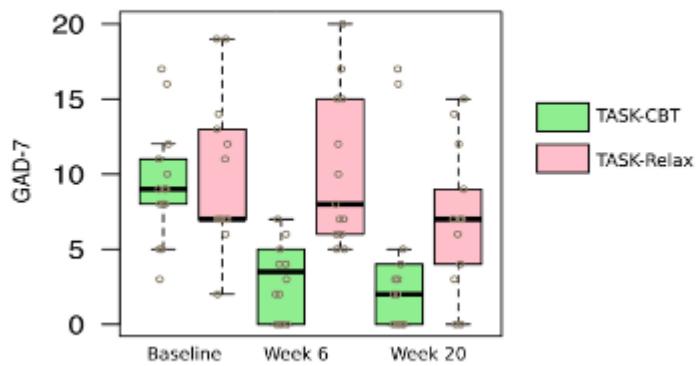
# Stroke project data



- 27 participants
- No normative data (no HC)
- ❖ Smartwatch (~1 month)
- ❖ Questionnaires (anxiety, fear)
- ❖ **Collected before + after different treatment**

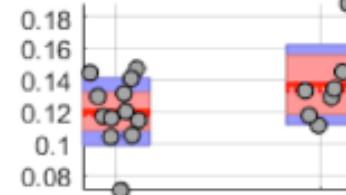
# Key findings

A) GAD-7 by treatment group

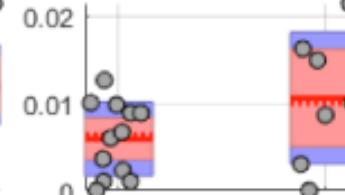


Smartwatch at T2

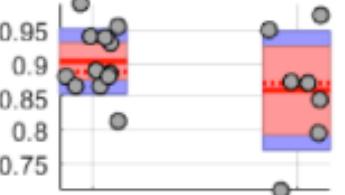
M10



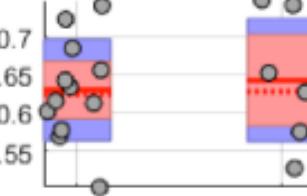
L5



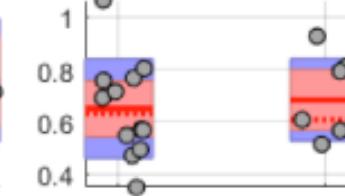
RA



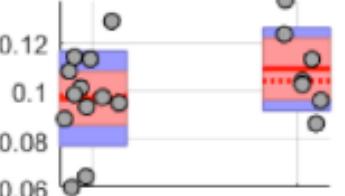
IS



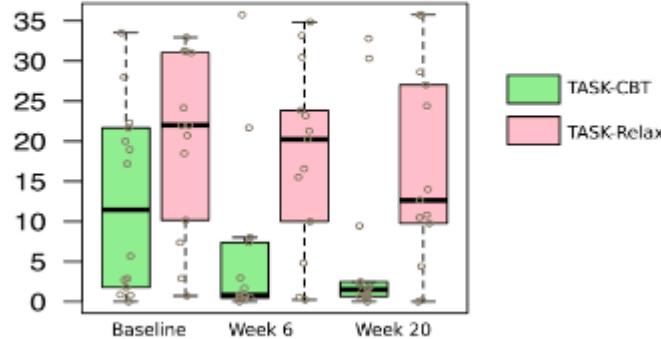
IV



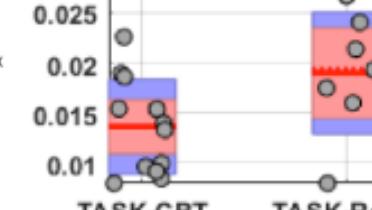
MDA



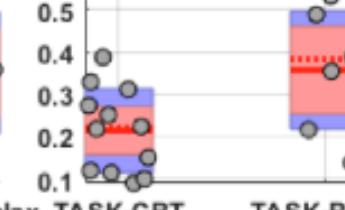
B) FQ-agoraphobia by treatment group



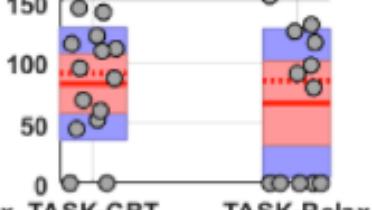
MNA



Sleep activity 50%



Std sleep dur. (min)



# Current and future work



## Wearables

- New algorithms
- New insights



## App-based monitoring

- PROMs
- Passive data



## The “invisibles”

- Electro-magnetic monitoring



# Conclusions

I just need  
the main ideas



- Easy to collect data often convey clinically useful information
- Moving towards **passively collected data**
- Fertile field to be developing algorithmic tools
- Need for interdisciplinary collaboration to make breakthroughs



# Data and code available:

← → C ⌂ <https://www.darth-group.com>

## Data Analytics Research and Technology in Healthcare (DARTH group)

HOME TEAM PROJECTS PUBLICATIONS SOFTWARE DATA TEACHING PHOTOS CONTACT



DARTH group mission

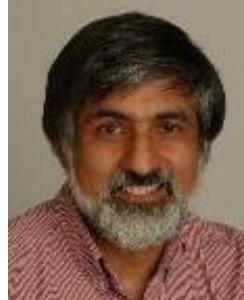
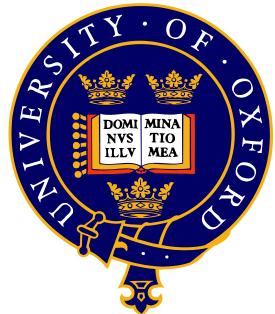
Ever-increasing healthcare provision demands strain national health systems globally, which struggle to meet patients' needs. We passionately believe we can design and provide effective solutions which will revolutionize contemporary healthcare delivery

- Data from different projects
- Toolboxes (Matlab code)
  - Time-series analysis
  - Actigraphy
  - ML methods

# Collaborators



# Acknowledgements



US, Spain,  
Greece,  
Australia, UK

