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Time-frequency deep learning model for sleep classification of dairy cows using polysomnography and RumiWatch data.

Chuanyi Guo[1,2], Emma Ternman[3], Xinjie Zhao[1], Kai Liu[2], Mutian Niu[1]

[1]*Animal Nutrition Group, ETH Zurich, Zürich, Switzerland.*

[2]*Department of Infectious Diseases and Public Health, City University of Hong Kong, Hong Kong SAR, China.*

[3] *Faculty of Biosciences and Aquaculture, Nord University, Steinkjer, Norway.*

What is sleep?

- Sleep is a recurring, reversible neuro-behavioral state of relative perceptual **disengagement from** and **unresponsiveness to** the environment (Mary and William, 1989).

For humans:

- Neural restoration
- Immune function
- Memory consolidation
- Maintaining overall health
- …

For cows:

Sleep is essential for mammals, yet remains poorly understood in cows.

Krueger et al., 2008; Cirelli and Tononi, 2008

Current gaps in cow sleep

Ground truth measurement:

- Visual Observation
  - Labor-intensive
  - Overestimation
- Electrophysiological Recording
  - Time-intensive
  - Annotator bias

Usability for on-farm applications

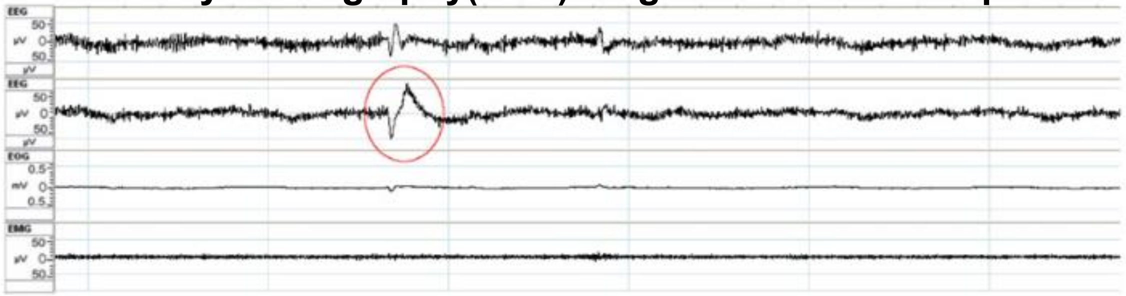
- PSG is impractical
- Alternative solution is needed

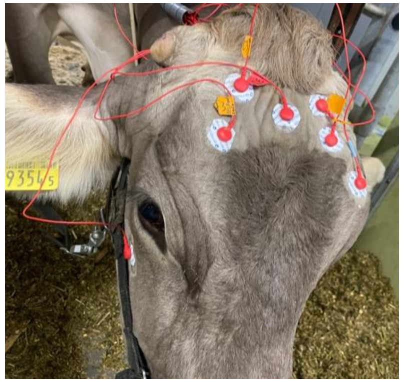
Comparison of Sleep Scoring Methods
(Ternman et al, 2014)

Sleep stages	Visual	Electrophysiological
NREM*	124 ± 17	20 ± 5
REM**	14 ± 4	10 ± 3

* NREM - Non-rapid eye movement
** REM – Rapid eye movement
*** Duration unit: Min

Polysomnography(PSG) Diagram of NREM Sleep





Objective

1. Propose an automated sleep classification method
2. Evaluate accessible sensors for sleep detection

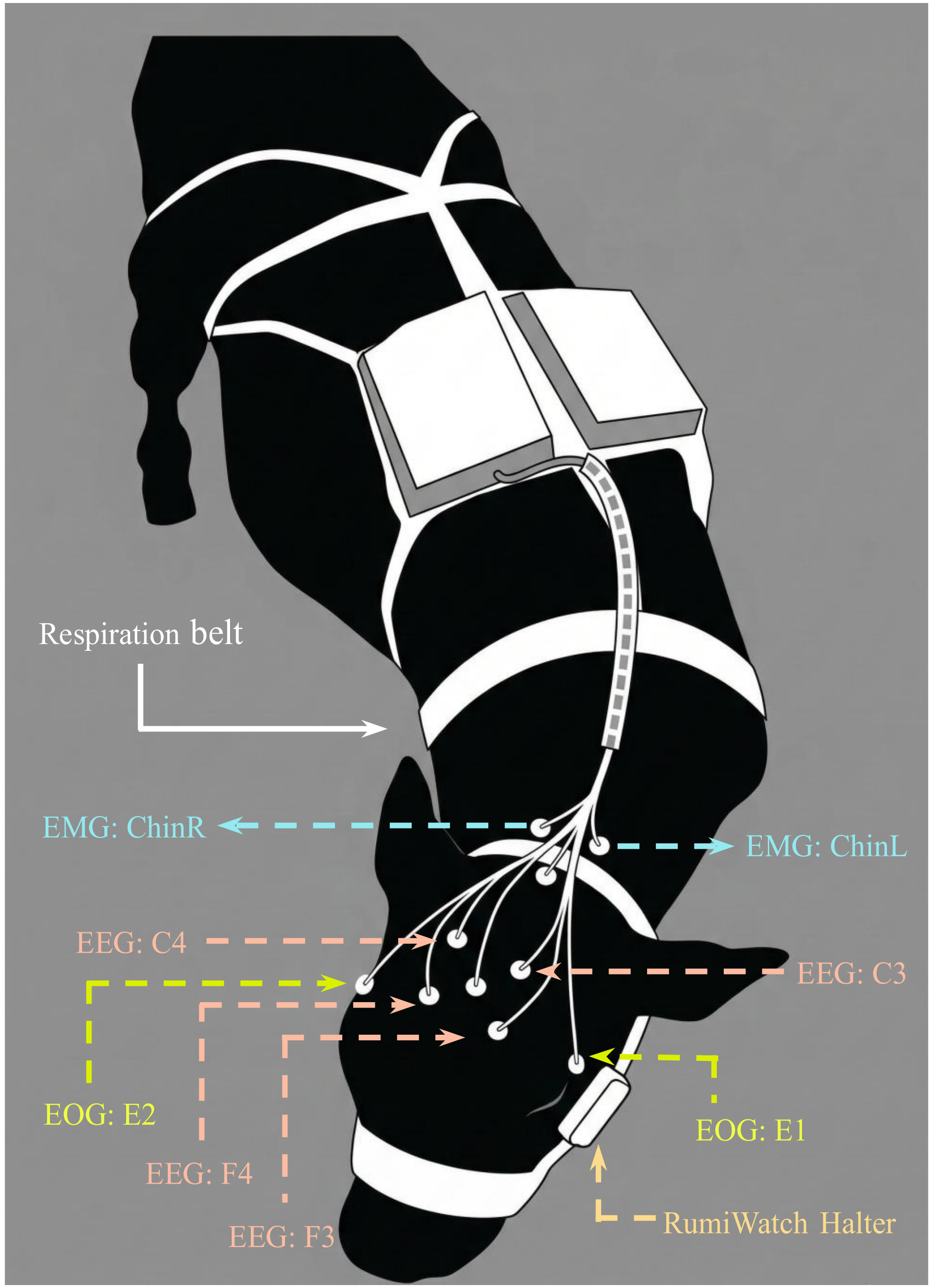
Data collection

9-Channel of Polysomnography (PSG)

- 4-channel – **Brain Activity (EEG)**
- 2-channel – **Muscle Activity (EMG)**
- 2-channel – **Eye Movement (EOG)**
- 1-channel – **Respiration (RS)**

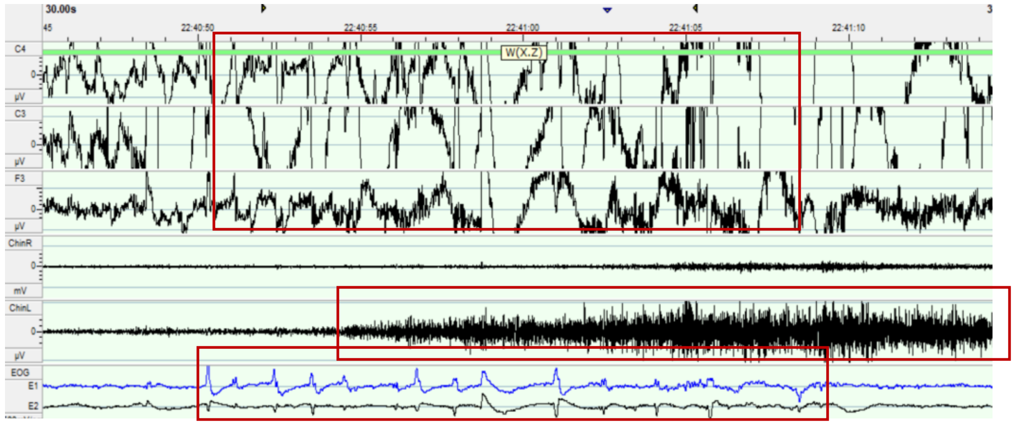
4-Channel of RumiWatch System (RWS)

- 1-channel – **Pressure (Jaw Movement)**
- 3-channel – **Accelerometers (X, Y, Z)**

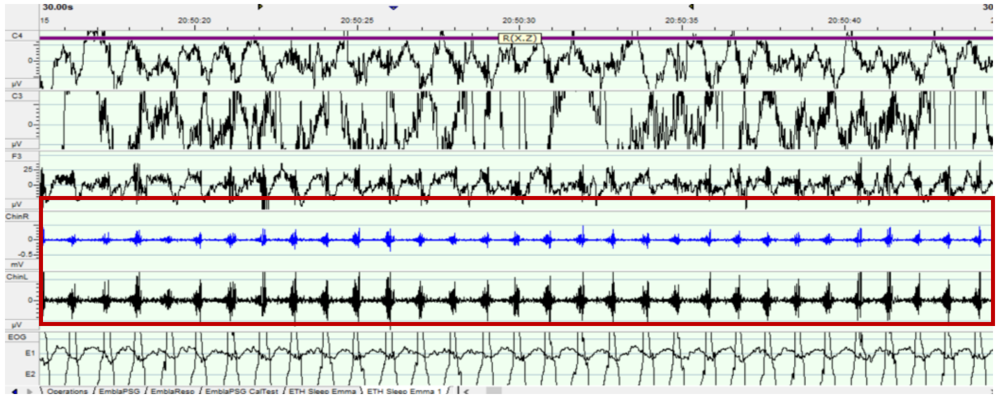


Data annotation

Wake 41.62%

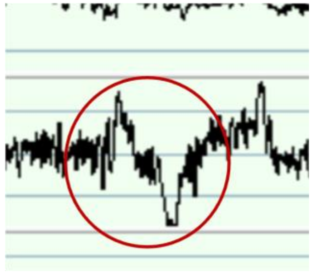


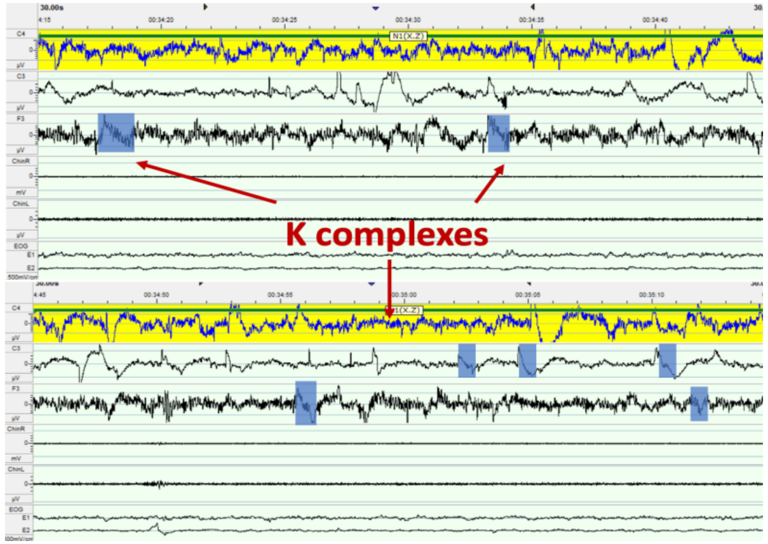
Rumination 45.59%



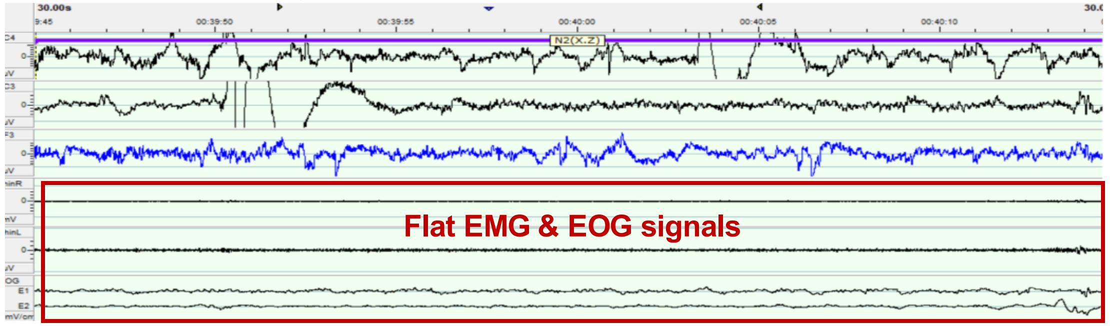
Sleep 12.79%

Drowsing

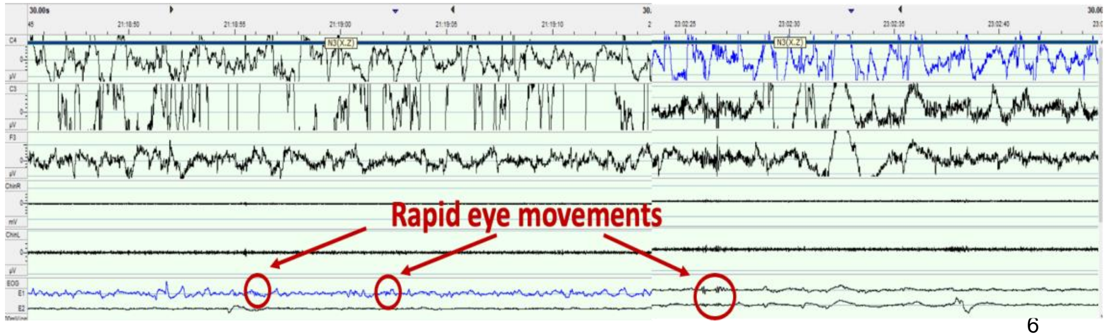




Non-Rapid Eye Movement (NREM)



Rapid Eye Movement (REM)



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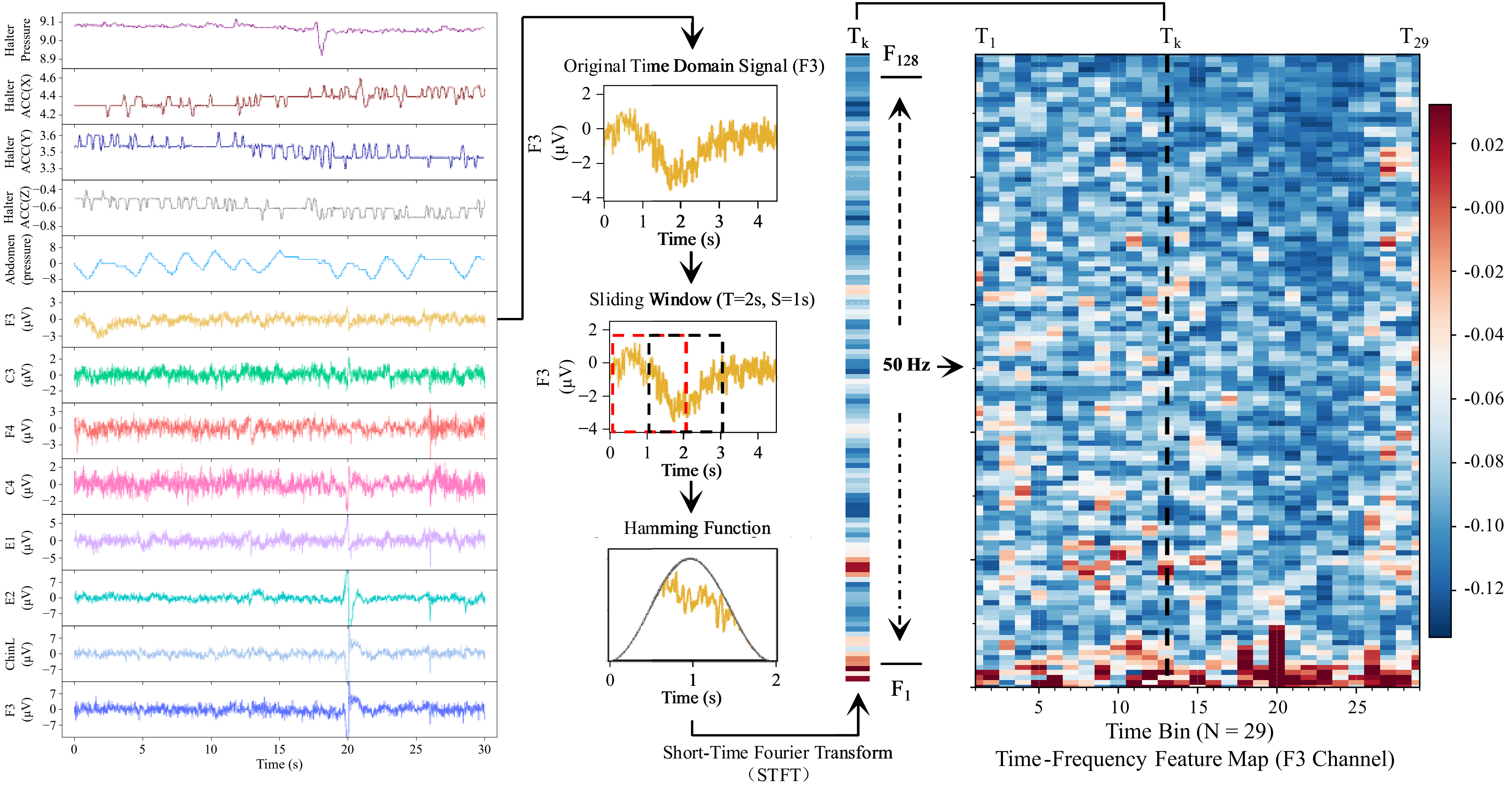
(Ternman et al, 2012)

Data annotation

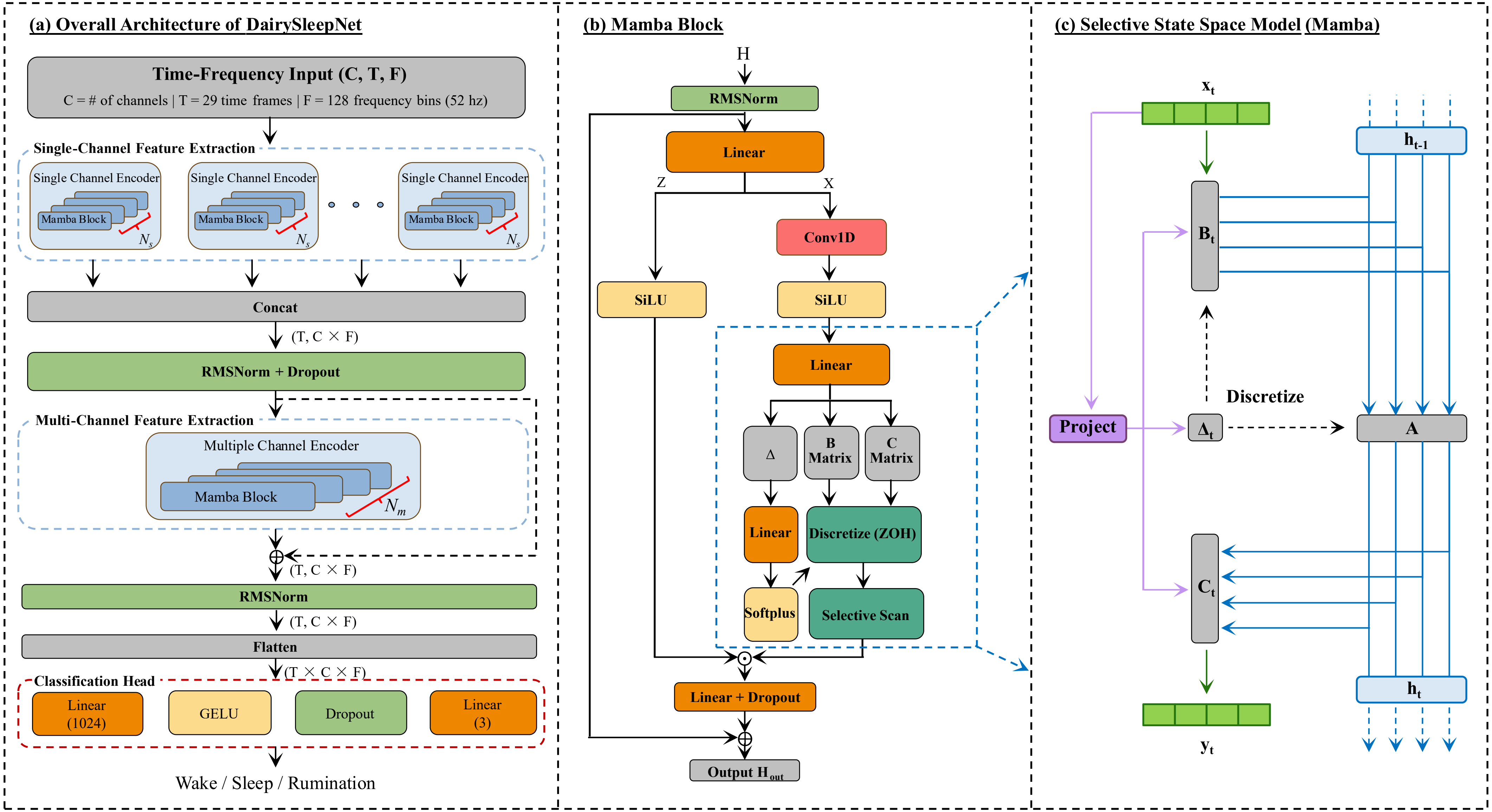
Cow ID	Behaviour Classes			Total Epochs	Duration (hour)
	Wake	Sleep	Rumination		
Cow 1	766	158	234	1,158	9.65
Cow 2	473	139	780	1,392	11.60
Cow 3	346	150	672	1,168	9.73
Cow 4	853	222	315	1,390	11.58
Cow 5	756	201	451	1,408	11.73
Cow 6	449	142	750	1,341	11.18
Cow 7	577	172	650	1,399	11.66

- **7** Cows, **77** hours data
- **1** epoch = a **30s** data segment

Data preprocessing – Time-frequency-based representations



DairySleepNet



$h_t = \bar{A}h_{t-1} + \bar{B}x_t$

$y_t = Ch_t$

$B = Linear_B(x_t)$

$C = Linear_C(x_t)$

$\Delta = softplus(Linear_\Delta(x_t))$

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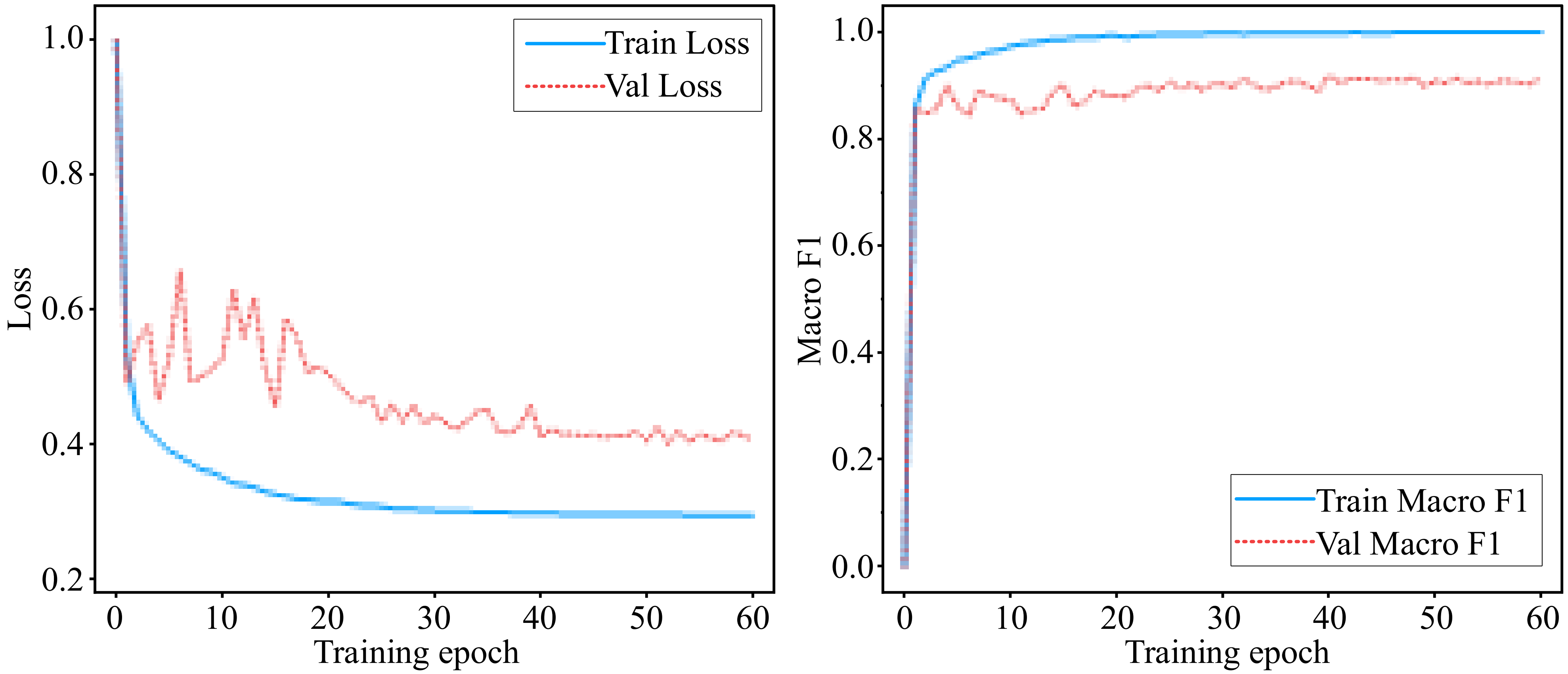
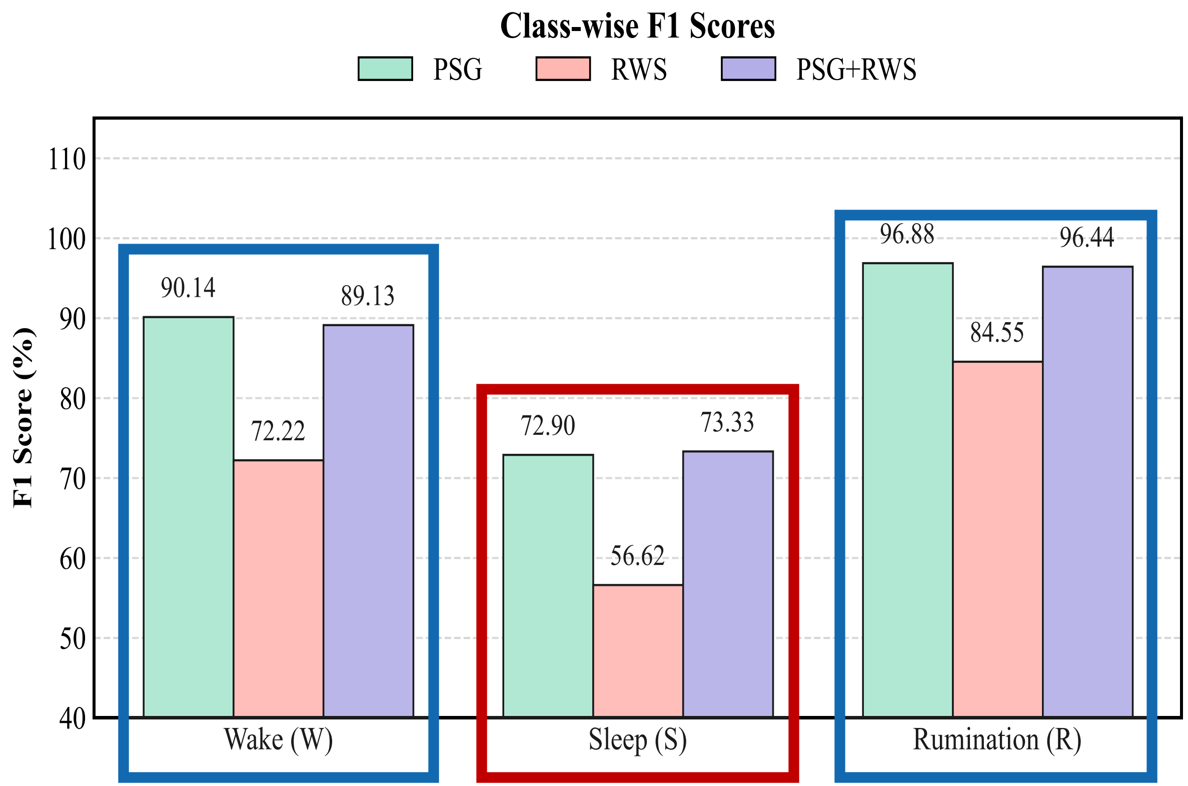
Model training

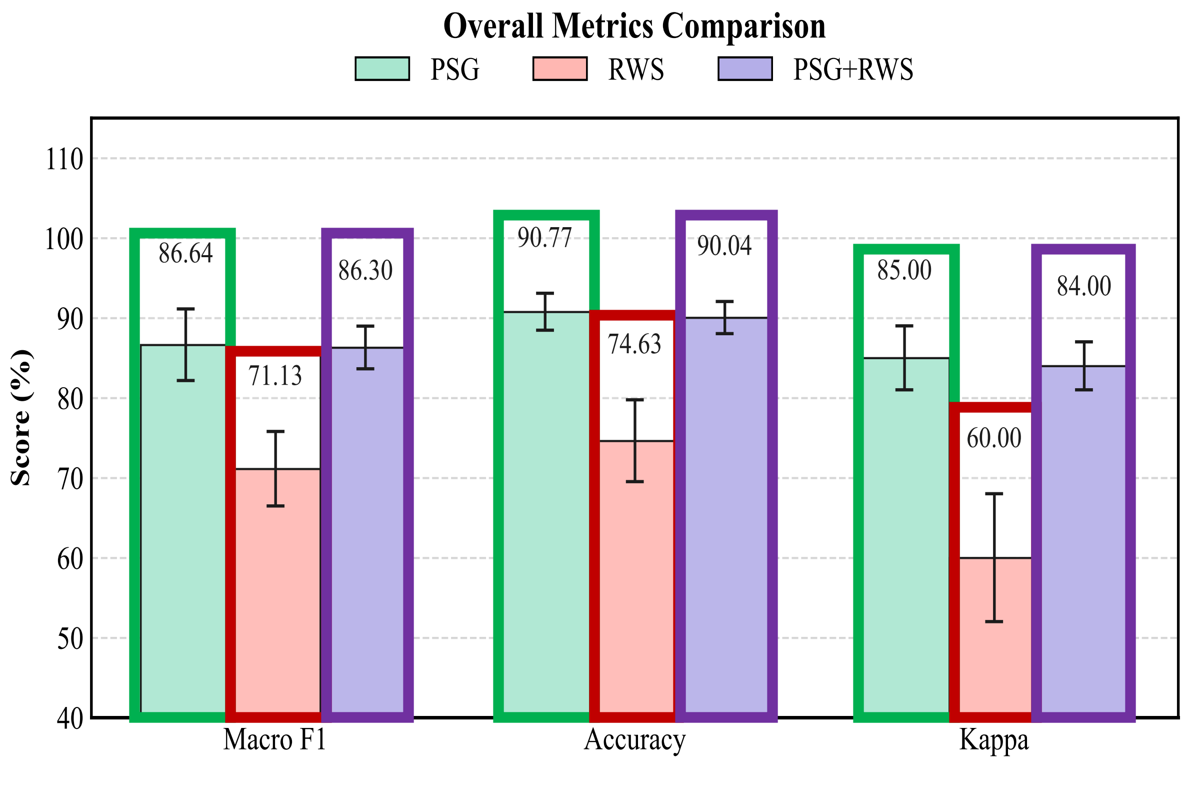
Animal-level 4-fold cross-validation, 10% of training set was held out as validation set

Training epochs was set to 200 with early stopping patience 20 epochs.



Model performance with different data inputs

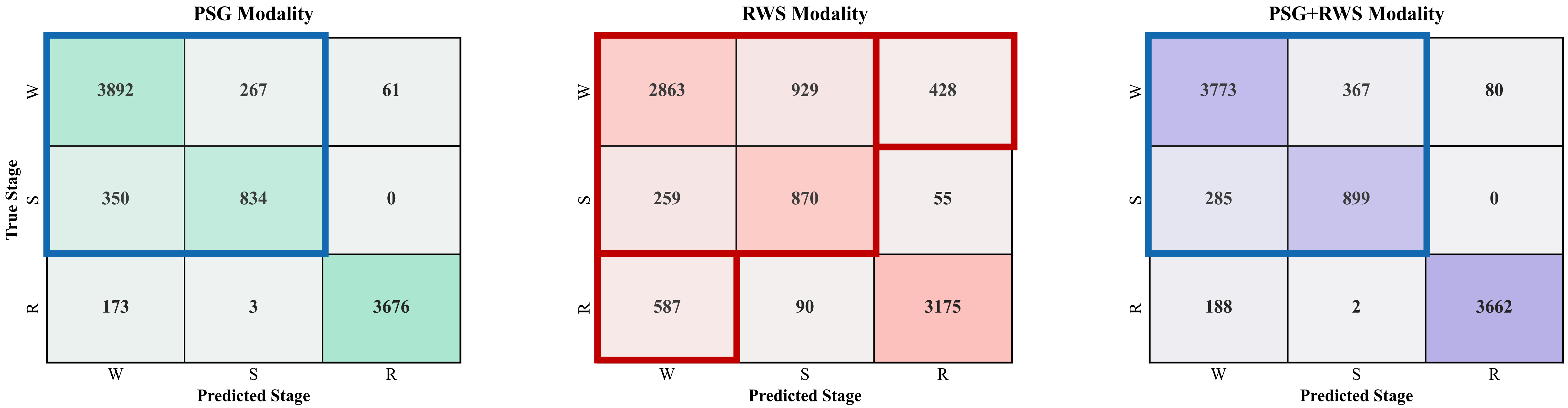




- Accurate classification for Wake / Rumination
- Challenge remains for Sleep

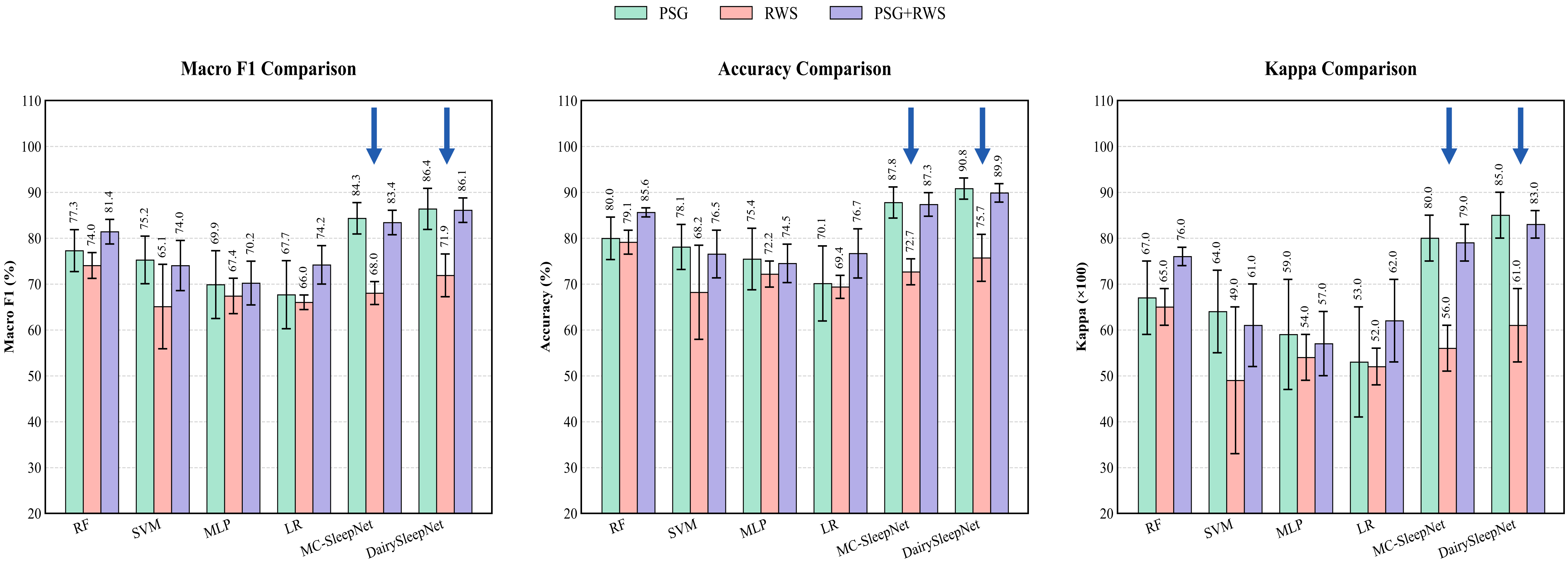
- PSG is the most informative data source
- RWS is insufficient for sleep classification
- PSG + RWS has less variances among folds

Model performance with different data inputs



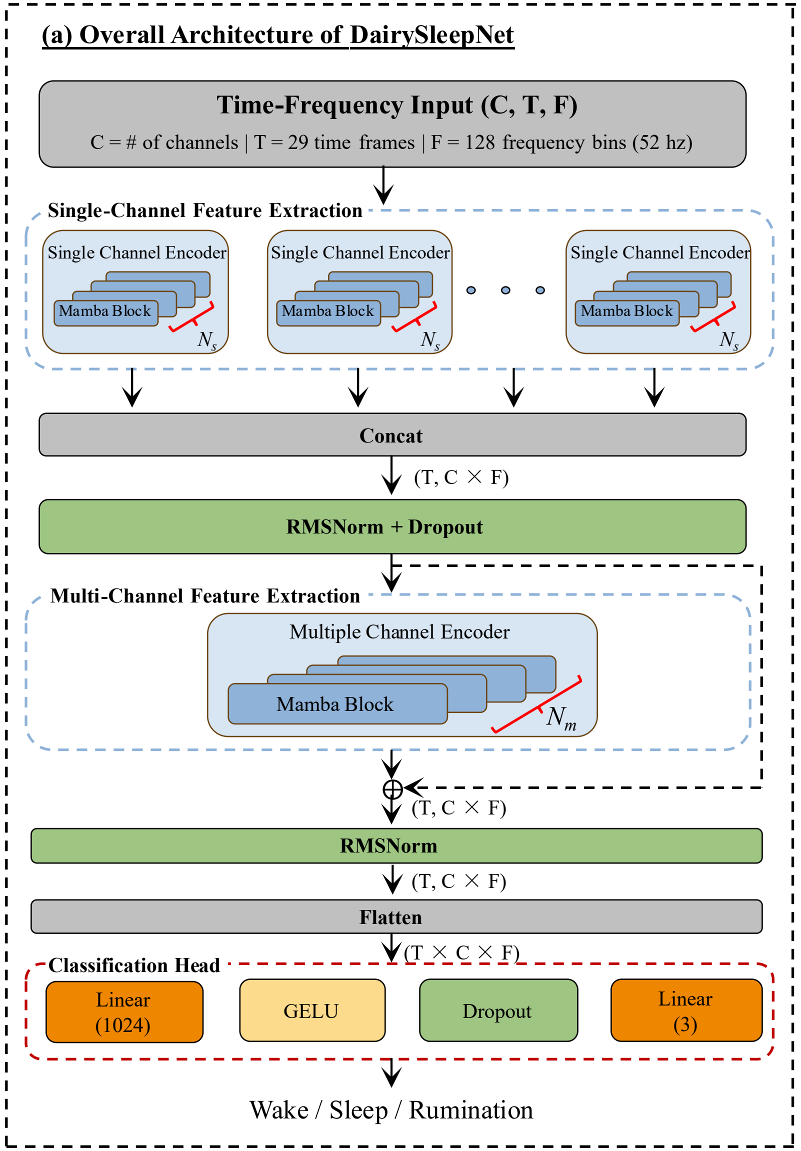
- Most of confusion arises between **Wake & Sleep**
- RWS has more mistakes classifying **Wake & Rumination**

Performance comparison with baselines



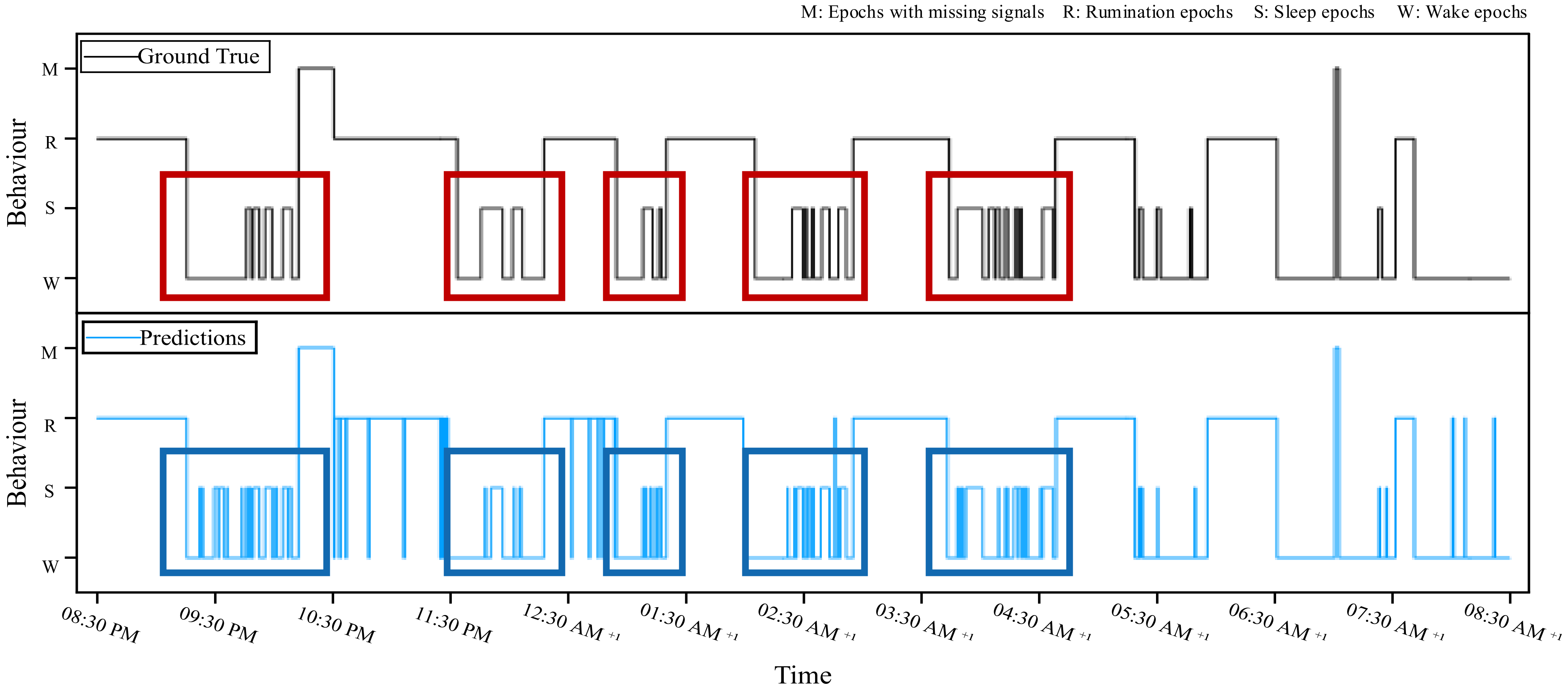
- ML method (Mean, Standard deviation, Root mean square, Range, Skewness, Kurtosis)
- Time-frequency representations are more informative than time-based feature representations

Sensitivity analysis



N_s	N_m	ACC	Macro F1	κ
4	2	88.64 ± 2.81	84.43 ± 4.12	0.81 ± 0.05
4	**4**	**90.80 ± 2.31**	**86.37 ± 4.48**	**0.85 ± 0.05**
4	8	89.58 ± 3.06	85.28 ± 4.81	0.83 ± 0.05
8	2	90.34 ± 2.23	86.09 ± 3.96	0.84 ± 0.04
8	4	90.23 ± 2.39	85.35 ± 4.24	0.84 ± 0.04
8	8	89.94 ± 2.72	85.42 ± 4.29	0.83 ± 0.05
16	2	89.65 ± 2.21	85.22 ± 3.53	0.83 ± 0.04
16	4	88.81 ± 3.03	84.68 ± 3.99	0.81 ± 0.05
16	8	90.29 ± 2.69	86.3 ± 4.06	0.84 ± 0.05

Hypnogram



- Overall pattern is well captured
- Mistake happens in transitions between **Wake & Sleep**

Takeaway message

- ***Selective state space model*** shows promising potential in classifying cow's sleep behavior.
- Time-frequency representations are ***more informative*** for sleep classification.
- Cow sleep is highly ***polyphasic***, making sleep-wake transitions much harder to capture than rumination.
- Next-generation farm sensors fusing ***multiple vital signs*** might be a more feasible alternative to PSG in routine farm settings

Thank you!

chuguo@ethz.ch