Forecasting the Onset Time of the Second Maximum of Proton Enhancements Using Solar-Wind Kinematics and a Quantum Regression Neural Network (RQNN)

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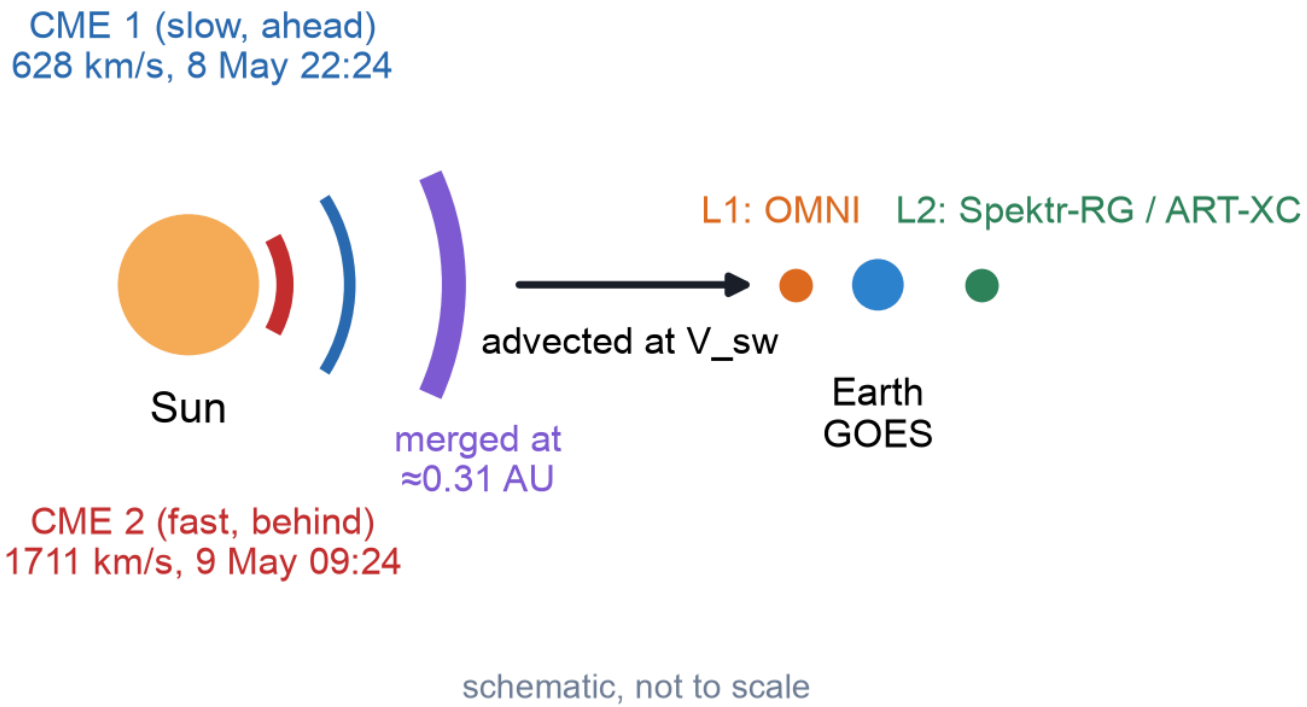
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Case study: the proton event of 10–11 May 2024

Outline

1. **Problem**
   where second proton maxima come from and why they are hard to forecast
2. **Method**
   CME catch-up kinematics (zeroth order) + RQNN residual correction
3. **Results**
   the 10–11 May 2024 event
4. **Analysis & limitations**
   honest validation, physical interpretation, what is missing
5. **Conclusions**
   summary, strengths and next steps

Where the second proton maximum comes from



- Protons are accelerated in **flares** and at **CME-driven shocks**
- They travel along the interplanetary magnetic field: **minutes to hours** to Earth
- A **second maximum** arrives with an interplanetary structure: shock / energetic storm particles (ESP), **merged (cannibalized) CMEs**
- Its timing is set by the **transport of the structure** in the solar wind → kinematic forecast is possible

Why forecast the second maximum, and why it is hard

Why

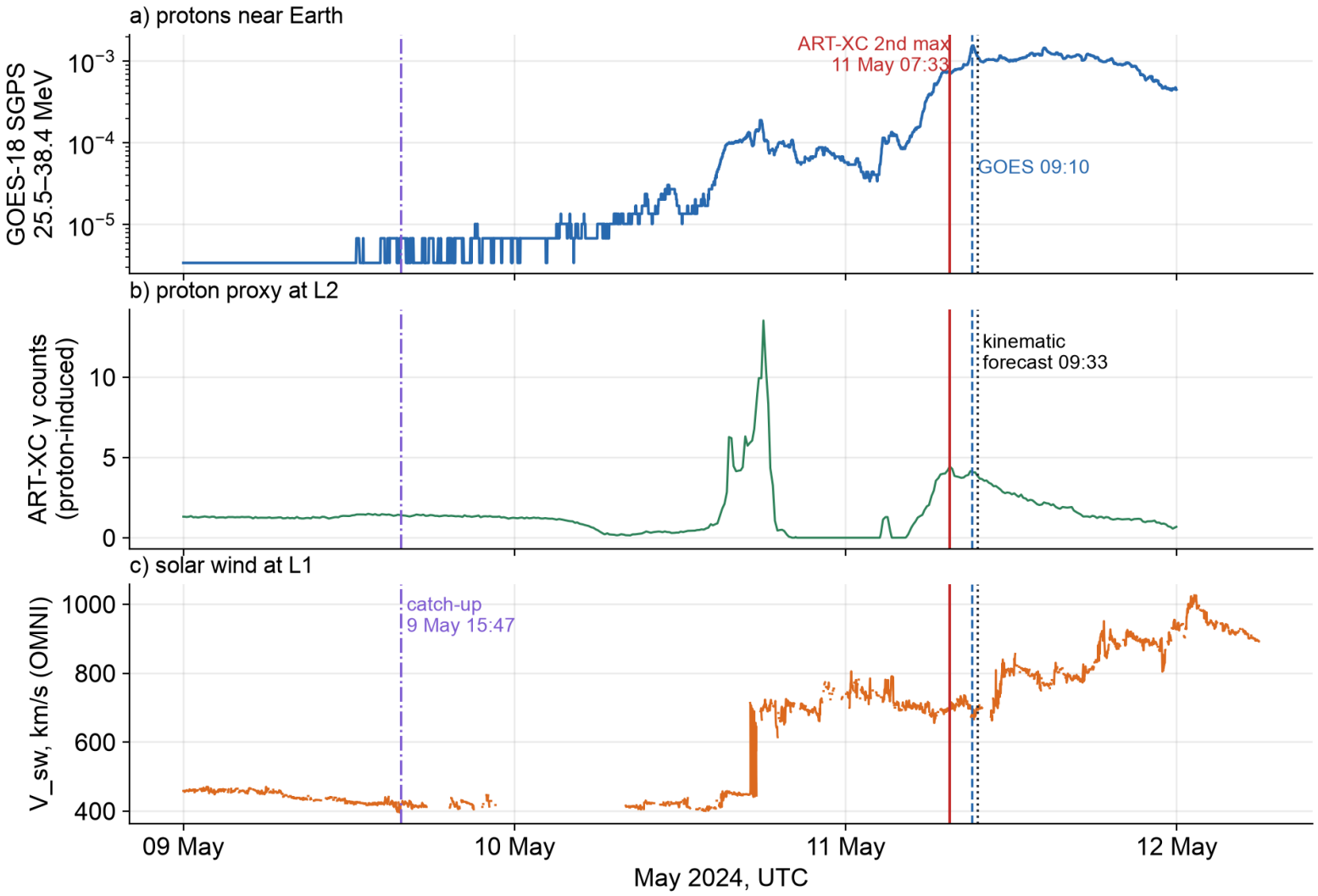
- Prolonged radiation exposure: spacecraft electronics, crews, polar aviation
- Operators need the **time** of the second peak, not only its existence
- Second maxima are tied to CME–CME interaction and shocks — more common when the CME rate is high (solar maximum)

Why it is hard

- **Nonlinear, non-stationary** links between proton flux and solar-wind parameters
- **Few events** with a clear second maximum → no training base for classical regression / neural networks
- CME speeds from coronagraphs are uncertain; solar wind changes during the event

> Approach: physics first (kinematic zeroth-order estimate), then a very small ML model that learns only the residual — the quantum regression model RQNN.

Case study: 10–11 May 2024



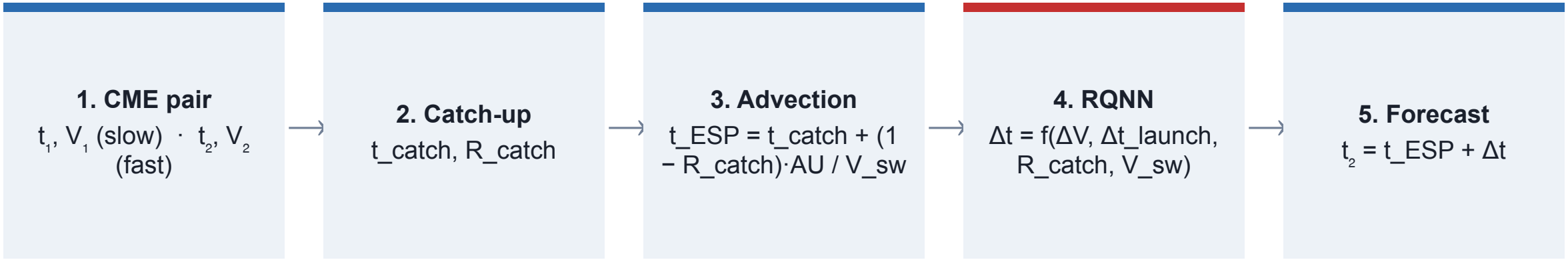
- CME 1: **08 May 22:24**, 628 km/s
- CME 2: **09 May 09:24**, 1711 km/s
- Shock at L1 on 10 May: V_sw jumps to ≈700 km/s
- Primary maximum (ART-XC): **10 May 18:03**
- Second maximum: ART-XC **11 May 07:33**; GOES 25–38 MeV **09:10**

Data: observations only

Source	Location	Quantity	Use
GOES-18 SGPS	geostationary orbit	protons 25.5–38.4 MeV, 1 min	observed second maximum (09:10)
ART-XC / Spektr-RG	L2	proton-induced γ counts (FULLSPIKE)	observed second maximum (07:33)
OMNI HRO	L1	V, n, T, Bz, 1 min	advection speed, features
LASCO-based CME list	coronagraph	launch time, linear speed, position angle	CME pairs, kinematics

- No synthetic flux profiles; preprocessing only on real samples
- ART-XC peaks found with the Schrödinger peak-detection method; GOES–ART-XC lag from cross-correlation

Pipeline: physics first, machine learning second



Zeroth order (steps 1–3): physical, interpretable, no training

Correction (step 4): learns only the residual Δt = t_obs − t_ESP

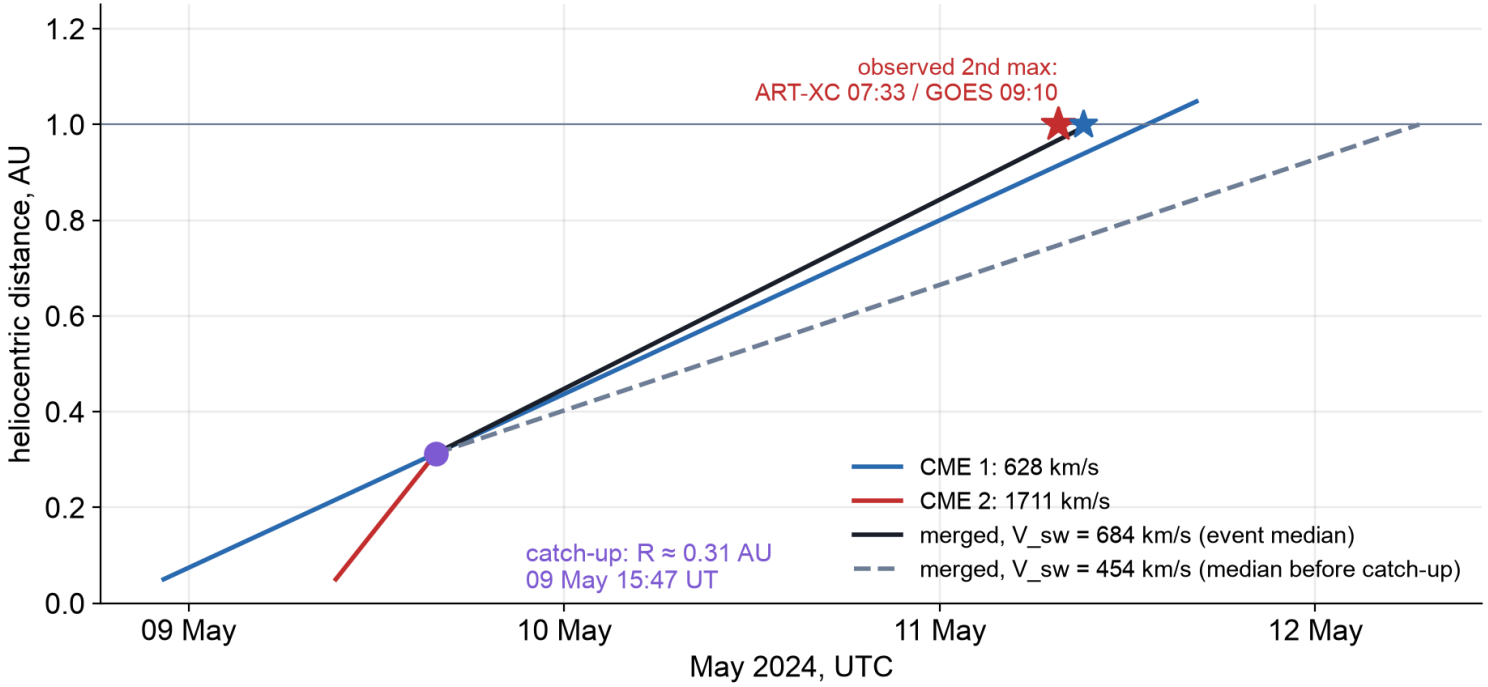
Residual learning: the model does not have to learn the physics — only what the simple physics misses.

Step 1: CME–CME catch-up kinematics

$$t_catch - t_2 = V_1 (t_2 - t_1) / (V_2 - V_1)$$

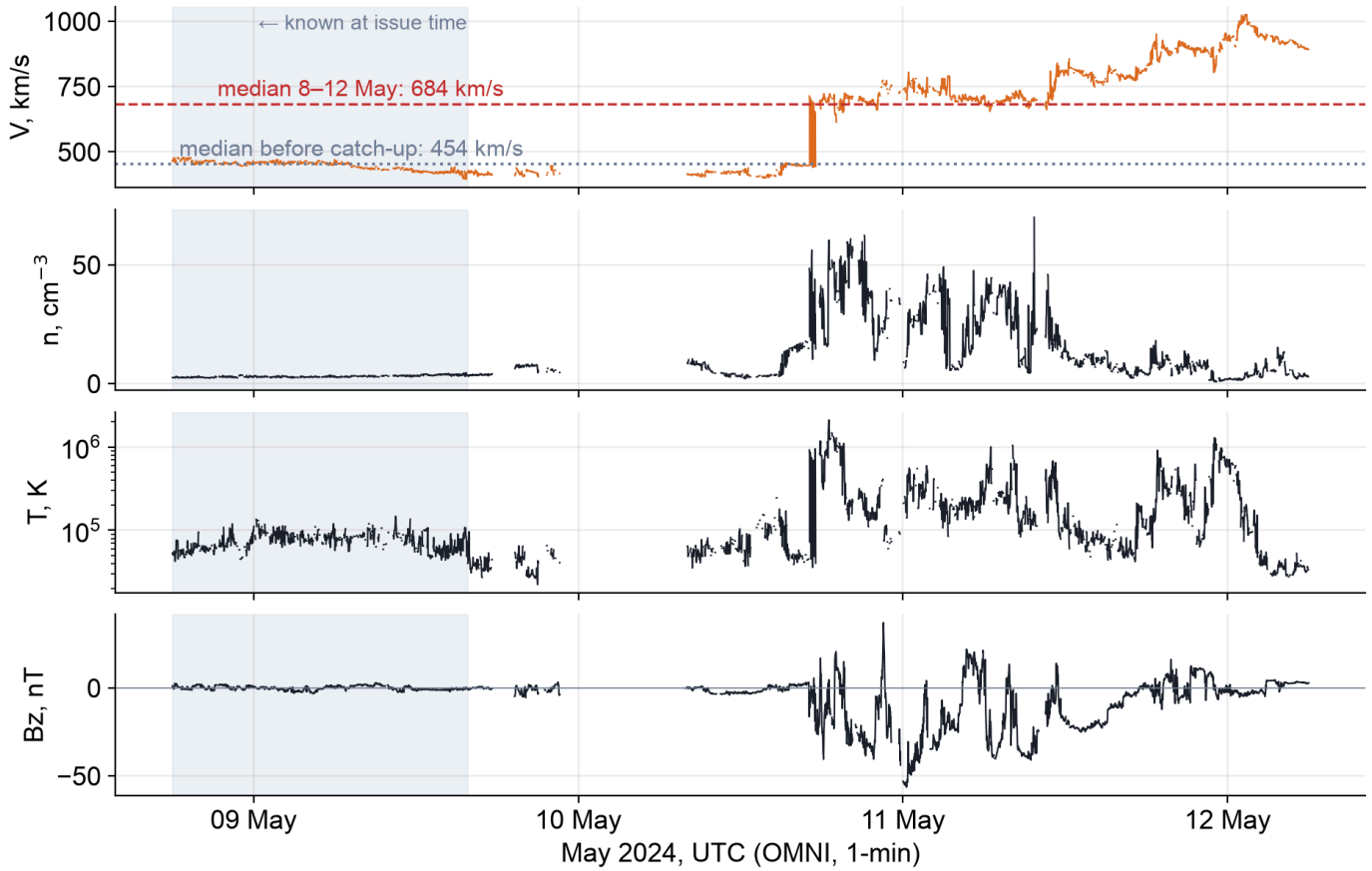
$$R_catch = R_0 + V_1 (t_catch - t_1), \quad R_0 = 0.05\ \text{AU}$$

- Δt_launch = **11.0 h**, ΔV = **1083 km/s**
- catch-up: **09 May 15:47 UT** at **R ≈ 0.31 AU**
- constant speeds, radial propagation



Step 2: advection of the merged structure to 1 AU

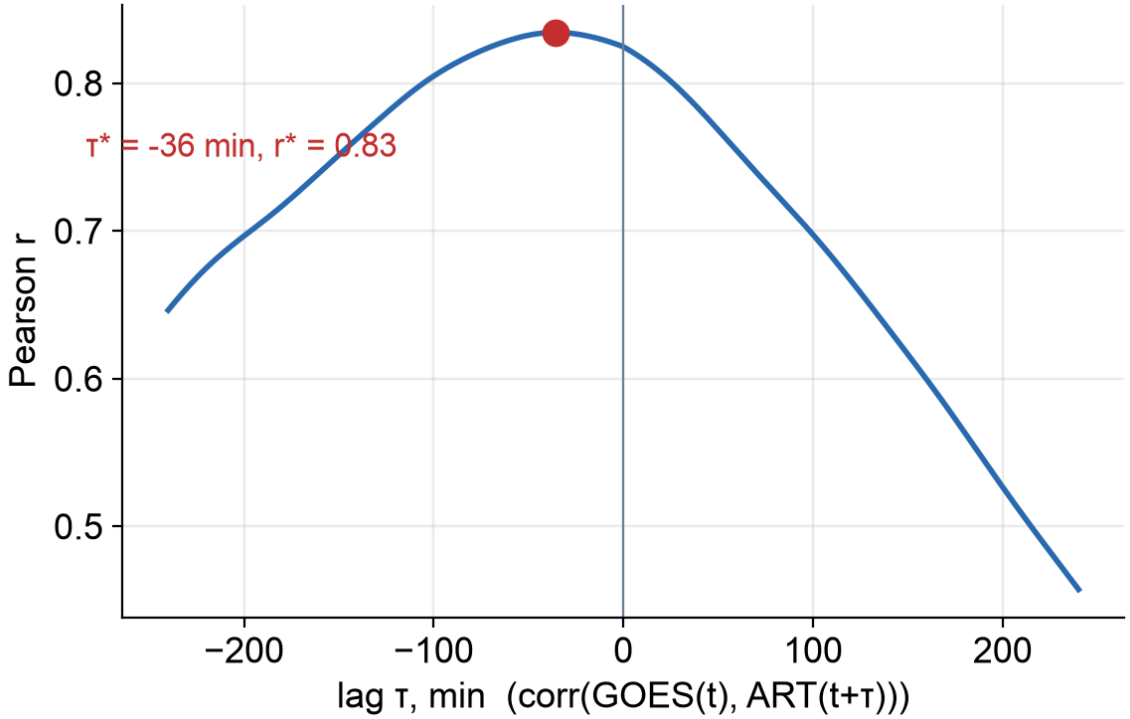
$$t_{ESP} = t_{catch} + (1 - R_{catch}) \cdot AU / V_{sw}$$



- OMNI median V_sw = **684 km/s** (8–12 May); n ≈ 5.4 cm^{-3}, T ≈ 8.7·10^4 K, Bz ≈ -1.0 nT
- → **t_ESP = 11 May 09:33 UT**
- Without V_sw no second peak is forecast

Note: the median includes the shocked wind measured **after** arrival at L1 (10 May ≈17 UT). Before catch-up: **454 km/s** (grey band).

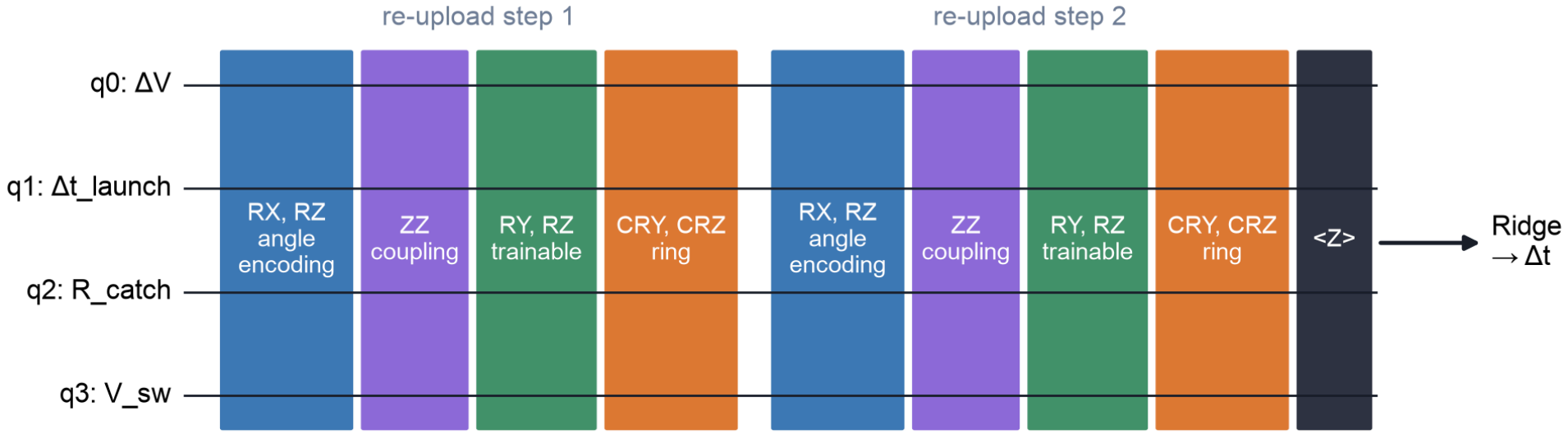
What is the observed second maximum?



Quantity	Value
ART-XC peaks (Schrödinger)	10 May 18:03 · 11 May 07:33
GOES 25–38 MeV second max	11 May 09:10
GOES–ART-XC lag τ*	-36 min (ART-XC leads)
max correlation r*	0.83
Earth–L2 convective time L/V_sw	≈ 37 min (magnitude only)

The two instruments agree on the profile, but the second maximum differs by 1.6 h between them. Reference used here (as in the abstract): ART-XC 11 May 07:33.

Step 3: RQNN — quantum regression of the residual



4 emulated qubits · inputs scaled to u in [0.05, 0.95] become rotation angles (phase shifts) · 48 circuit parameters + Ridge read-out

- Target: **Δt = t_obs − t_ESP**
- 4 features → 4 emulated qubits; scaled features become **rotation angles (phase shifts)**
- 2 data re-uploading steps; read-out ⟨Z⟩ → Ridge
- 48 circuit parameters + 4-weight read-out
- Simulated classically (PennyLane default.qubit)
- No quantum hardware, **no quantum advantage claimed**

Training set and fitting

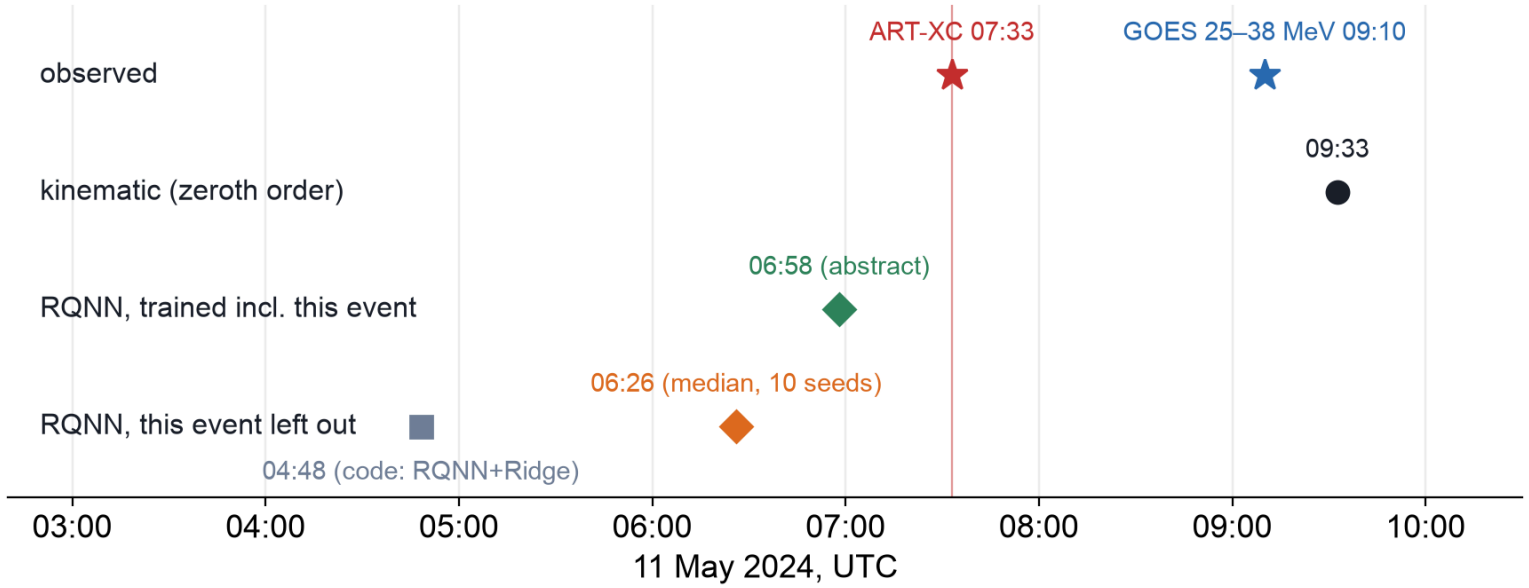
CME pair (launches)	ΔV, km/s	Δt, h	R_catch, AU	residual, h
08 May 22:24 → 09 May 09:24 (main)	1083	11.0	0.31	-1.99
07 May 15:48 → 08 May 19:12	251	27.4	0.42	-4.41
08 May 02:36 → 08 May 22:24	279	19.8	0.42	-2.59
08 May 12:24 → 09 May 09:24	1247	21.0	0.37	+0.15
08 May 12:24 → 09 May 12:24	330	24.0	0.70	-9.15
08 May 19:12 → 09 May 09:24	1189	14.2	0.31	-2.22
08 May 19:12 → 09 May 12:24	272	17.2	0.68	-9.27
08 May 19:24 → 09 May 09:24	1411	14.0	0.17	-7.11

- 8 CME pairings from the 7–9 May list (catch-up inside 1 AU, |residual| ≤ 10 h) + 8 jittered copies
- **All residuals are measured against the same peak** (11 May 07:33): one event, 8 hypotheses
- Loss: pseudo-Huber on tanh-scaled target; target = 0.55·Ridge + 0.45·observed
- Optimiser: L-BFGS-B, **8 iterations**

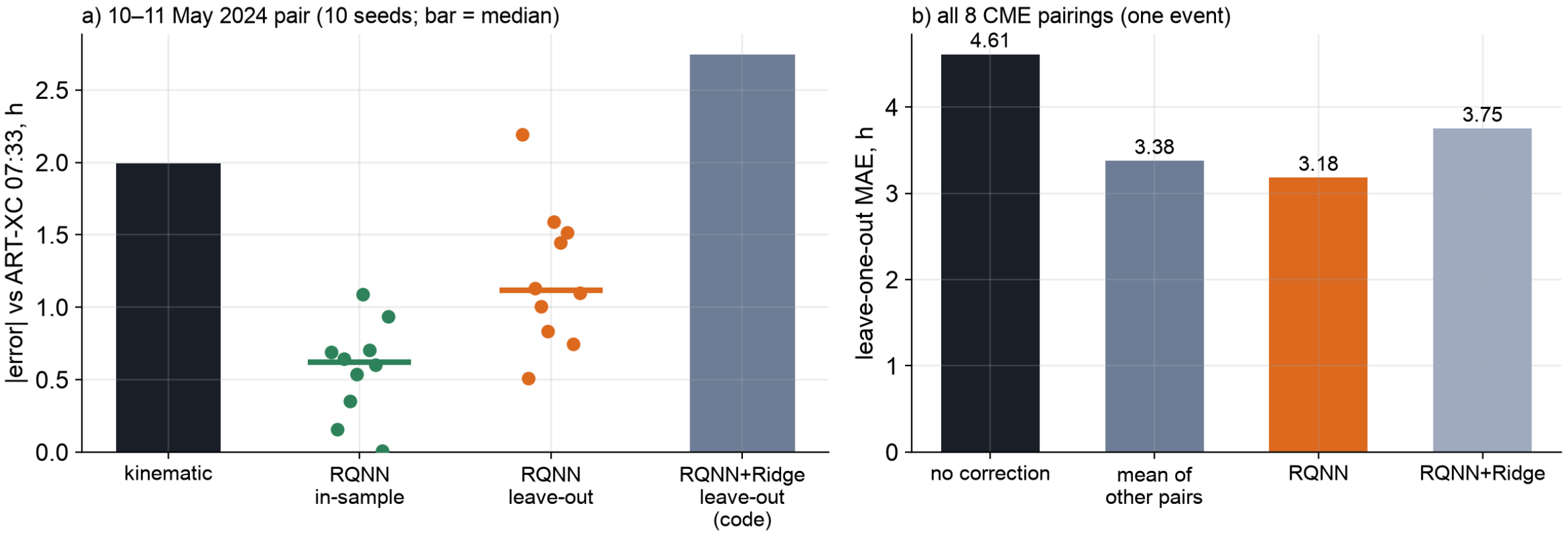
Result as reported in the abstract

	Second maximum	Error vs ART-XC 07:33
Kinematic (zeroth order)	11 May 09:33	+2.0 h
RQNN (abstract)	11 May 06:58	−0.6 h
Gain		1.4 h

Caution: this RQNN was trained **including this very pair** — the 0.6 h describes the fit, not a forecast.



Is it a forecast? Leave-this-pair-out test



- In-sample: median error **0.6 h** (10 seeds). Pair left out: median **1.1 h** (0.5–2.2), better than kinematics in **9/10** seeds → honest gain ≈ **0.9 h**, not 1.4 h
- RQNN+Ridge leave-out (code): **2.75 h** — worse than kinematics. All 8 pairings: RQNN 3.18 h vs mean of others 3.38 h

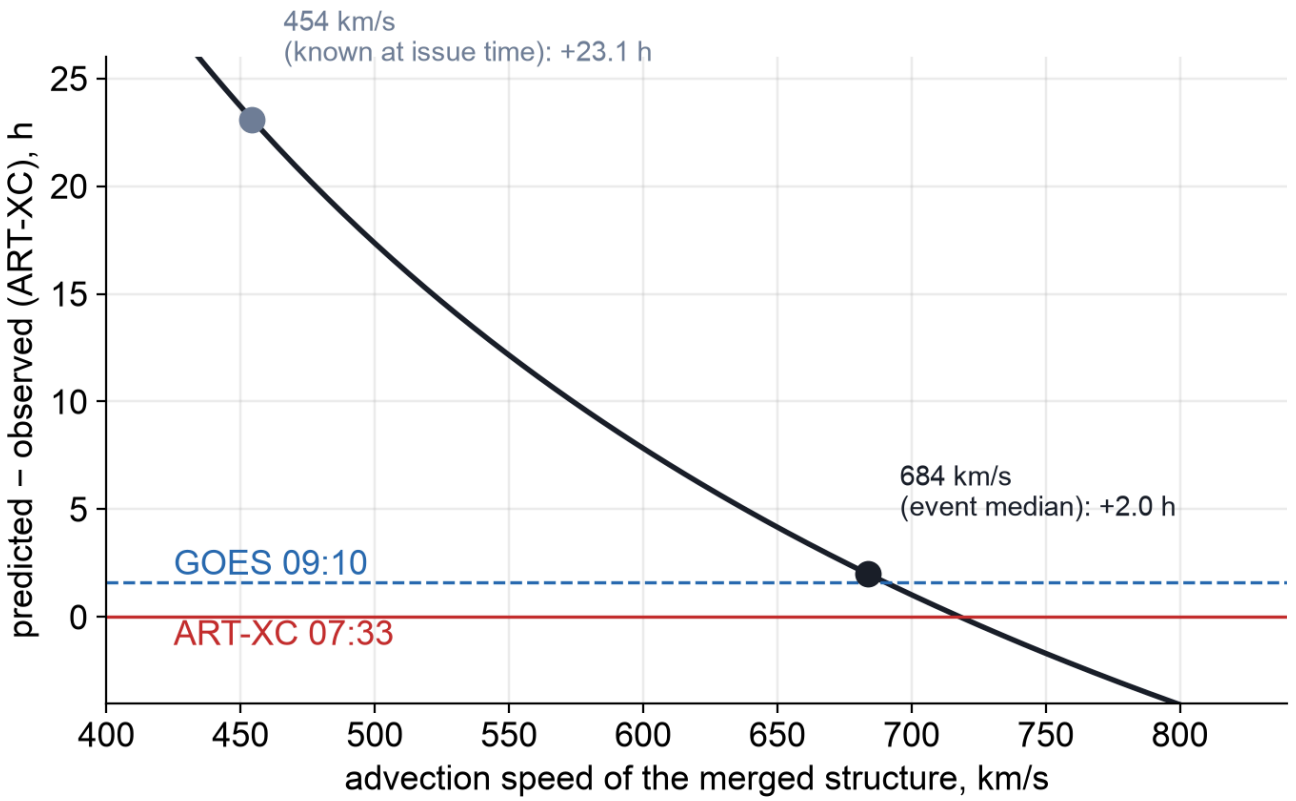
Which reference time?

Reference (second maximum)	Time, 11 May	Kinematic error	RQNN (abstract) error
ART-XC (proton proxy, L2)	07:33	2.0 h	0.6 h
GOES-18 25–38 MeV	09:10	0.4 h	2.2 h
GOES >10 MeV (15-min median)	14:34	5.0 h	7.6 h

Needed: a consistent, per-channel definition of the second maximum (e.g. onset or half-rise time).

- The definition of the second maximum changes the answer by **hours**
- A model trained on ART-XC moves the forecast **away** from GOES
- Higher energies peak earlier: ART-XC < GOES 25–38 MeV < GOES >10 MeV

Hindcast or forecast: what was known when?



- Earliest issue time: catch-up, **9 May 15:47** (lead ≈ 40 h)
- V_sw known then: **454 km/s** → 12 May 06:39 (**+23 h**)
- 684 km/s = median over 8–12 May incl. post-arrival wind → **hindcast**
- 1 % in speed ≈ **0.4 h**; ART-XC time ↔ **718 km/s** (+5 %), GOES ↔ 690 km/s

> The advection speed dominates the error budget.

Physical interpretation

Observation	Interpretation
Residual −2.0 h (vs ART-XC)	merged, shock-driven structure ≈5 % faster than the event-median wind; ESP peak at the shock, ahead of the ejecta
ART-XC (at L2) leads GOES by 36 min	$\|\tau^*\|$ matches the Earth–L2 convective time (≈37 min), but the sign is opposite to convection → likely the higher-energy response of the γ proxy
ART-XC 07:33 < GOES 25–38 MeV 09:10 < GOES >10 MeV 14:34	higher energies peak earlier (velocity dispersion / transport) — single event
Drag-based model, $\gamma = 2 \cdot 10^{-8}$ km^{-1}	no catch-up before 1 AU → the zeroth-order picture itself is model-dependent
No V_sw → no second peak in the kinematic model	the second maximum is a solar-wind transport phenomenon

Limitations

Limitation	Evidence	Next step
One event; 8 rows = pairings of it	all residuals vs the same peak	multi-event dataset
Abstract value is in-sample	leave-out: 1.1 h, not 0.6 h	leave-one-event-out
Model selection uses the truth	code picks full fit or leave-out by closeness to t_obs	fixed selection rule
Look-ahead in V_sw	684 km/s includes post-arrival wind; 454 km/s at issue time	issue-time inputs only
Ambiguous reference	07:33 / 09:10 / 14:34 by channel	per-channel definition
Very short optimisation	8 iterations; seed spread 0.5–2.2 h	seed ensembles
Kinematics simplified	constant speeds; no direction check; DBM: no catch-up	DBM / ENLIL zeroth order

Next steps

Multi-event dataset	second maxima with CME–CME interaction, cycles 24–25
Strict protocol	leave-one-event-out; inputs available at issue time only
Baselines	ridge, Gaussian process, boosting on the same splits
Better zeroth order	drag-based model / ENLIL arrival times
Consistent target	per-channel second-maximum definition + uncertainty intervals

Conclusions

Summary

- Catch-up at **≈0.31 AU** + advection → **11 May 09:33**: ART-XC 07:33 (2.0 h), GOES 09:10 (0.4 h)
- RQNN fits this event to **0.6 h**; with the event left out: **≈1.1 h** (better than kinematics in 9/10 seeds)
- With issue-time solar wind the kinematic estimate is **+23 h** off → advection speed is the key input

Strengths

- Physically interpretable zeroth order
- Residual learning needs **very few samples**
- Compact model: 4 qubits, 48 parameters, classical emulation
- Transparent validation → clear path to a real forecast

> Thank you — questions welcome.