

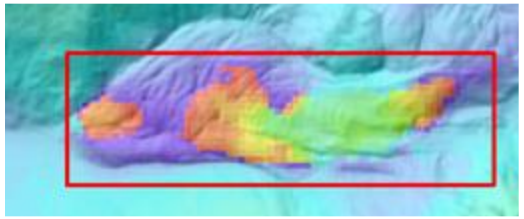
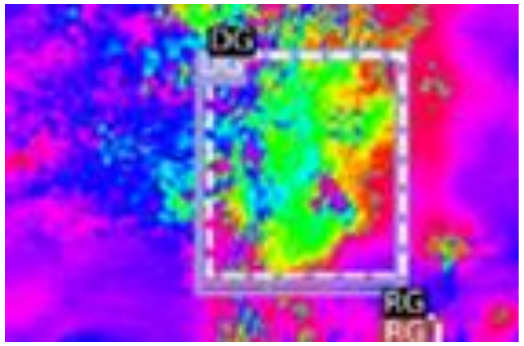

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JAGIELLONIAN UNIVERSITY IN KRAKÓW

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Automated detection of active mass movements in SAR wrapped interferograms using a geomorphology-constrained YOLO-based CNN

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UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

National Research Council of Italy

Slow mass movements

Wide ranges of:

→ **size** (10^3-10^8 m^3) and **velocity** (10^{-3}-10 m/yr)

→ materials, topography, landcover

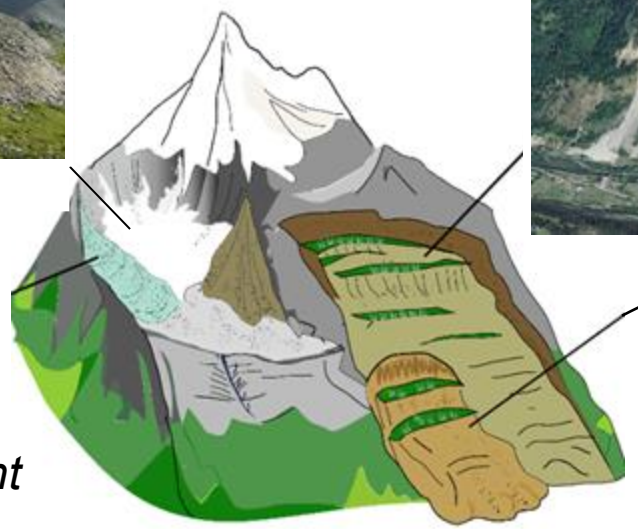
→ impacts on **landscape**, **geohazard**, **climate change** studies

need to **rapidly detect** and **classify active processes** over **wide areas** for:

inventory update, hazard and risk, assessment, regional monitoring, candidate selection for site-specific investigations

rock glacier

large rockslide



e.g. alpine environment

debris slide

Current regional-scale assessments:

→ **geomorphology + remote sensing**

accurate, expert-based,
time consuming, long to update.

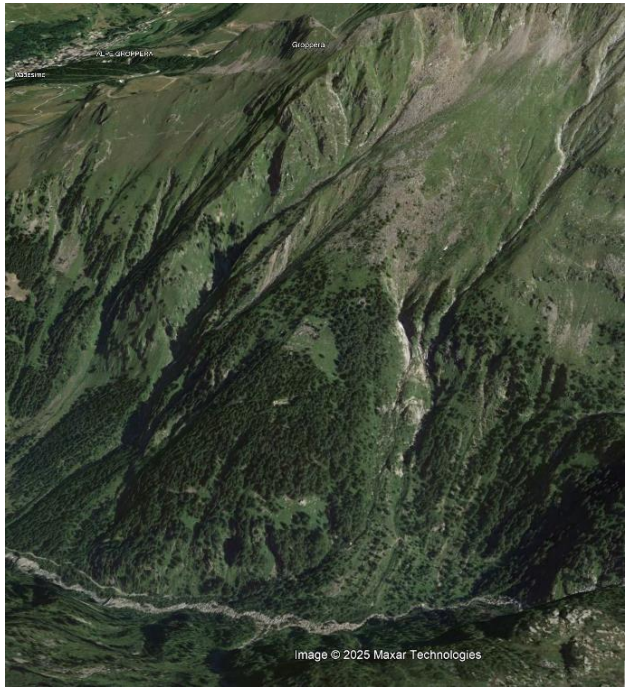
→ **Artificial Intelligence**

optical: miss slow movements

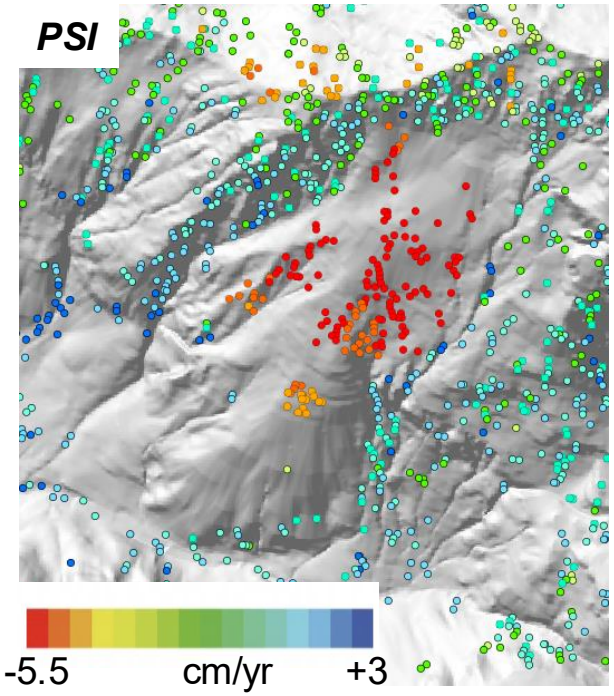
Automated mapping with InSAR: which data?

→ **MT-InSAR**: **accurate** (mm/yr) but **sparse data, missing fast** movements, suffering **unwrapping errors**

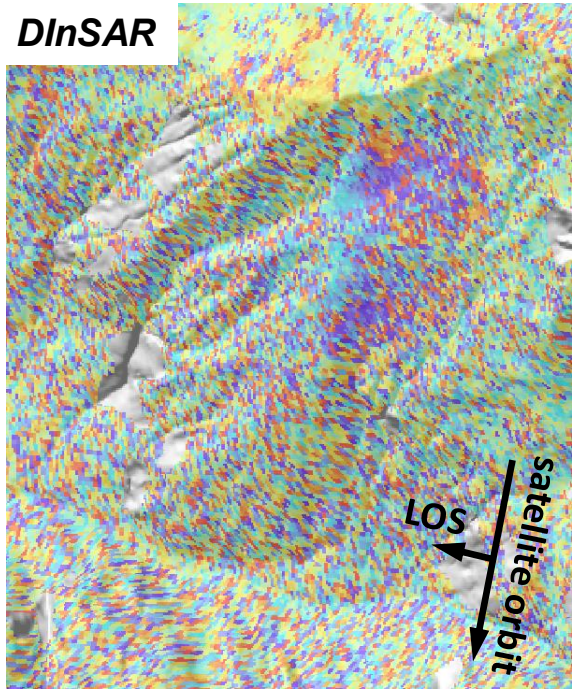
→ **DinSAR: interferogram** (phase), less accurate but **spatially distributed** and **preserve most information**



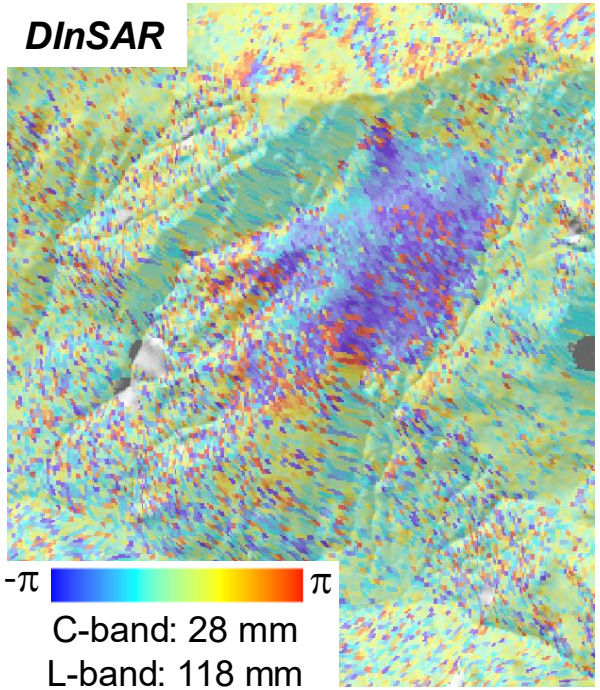
Fraciscio (Valle Spluga)



*Sentinel-1 (C-band) – **2015-2017***



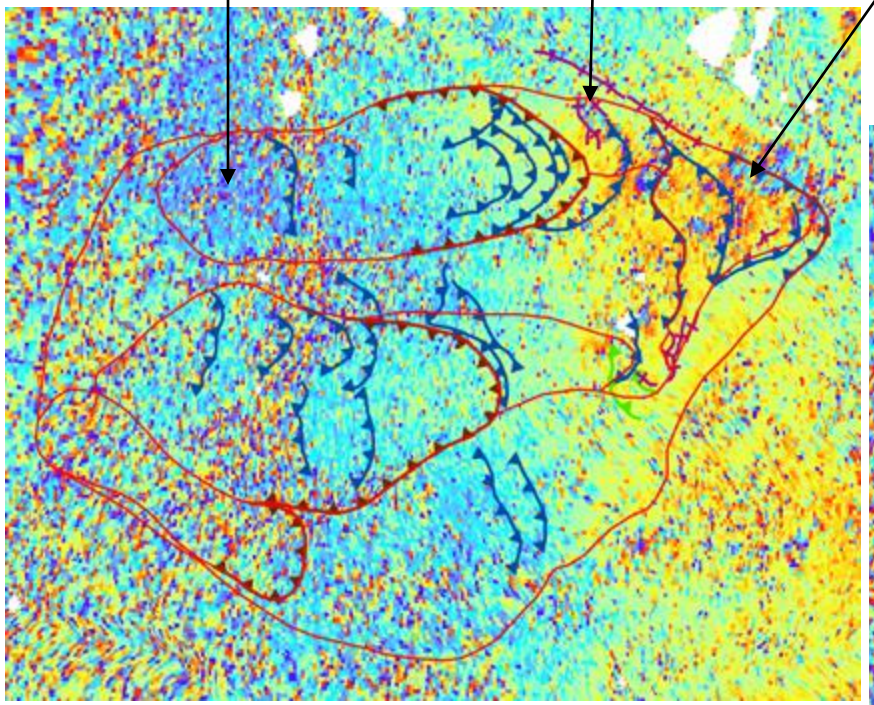
*Sentinel-1 (C-band) – **1 year***



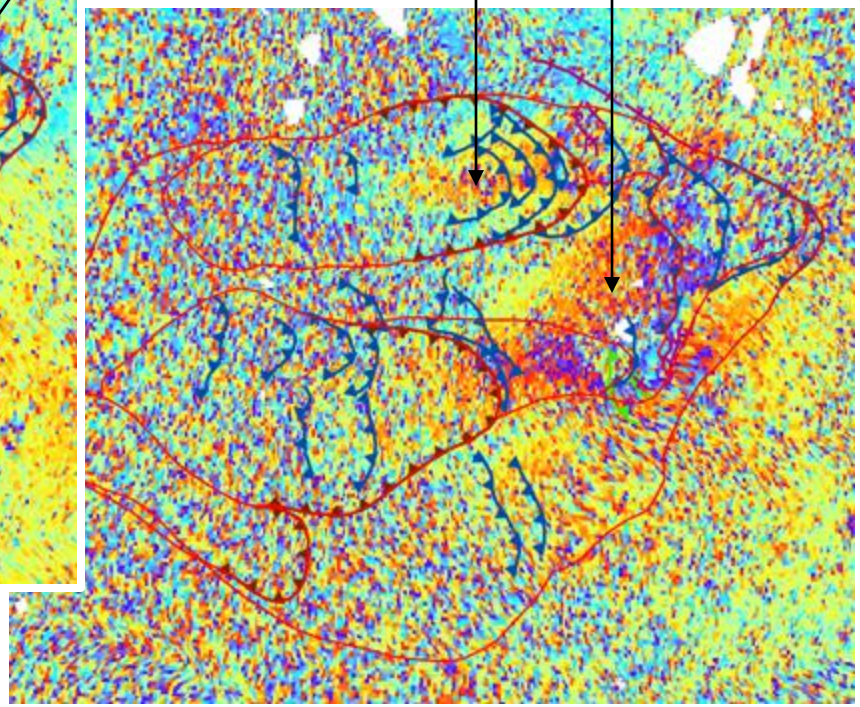
*SAOCOM-1 (L-band) – **1 year***

DInSAR: the importance of temporal baseline

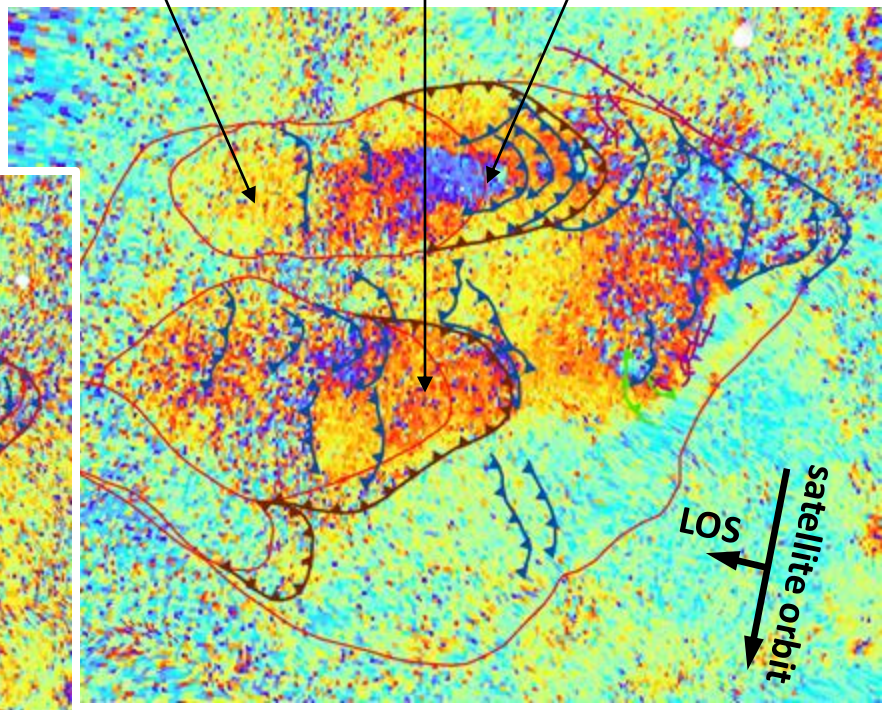
Different temporal baselines capture different surface processes!



*Sentinel-1 (C-band) – **24 days***



*Sentinel-1 (C-band) – **3 months***



*SAOCOM-1 (L-band) – **1 year***

$-\pi$ π

C-band: 28 mm
L-band: 118 mm

M.Mater (Madesimo, Valle Spluga)

esa **MODULATE**

MIRAGE approach

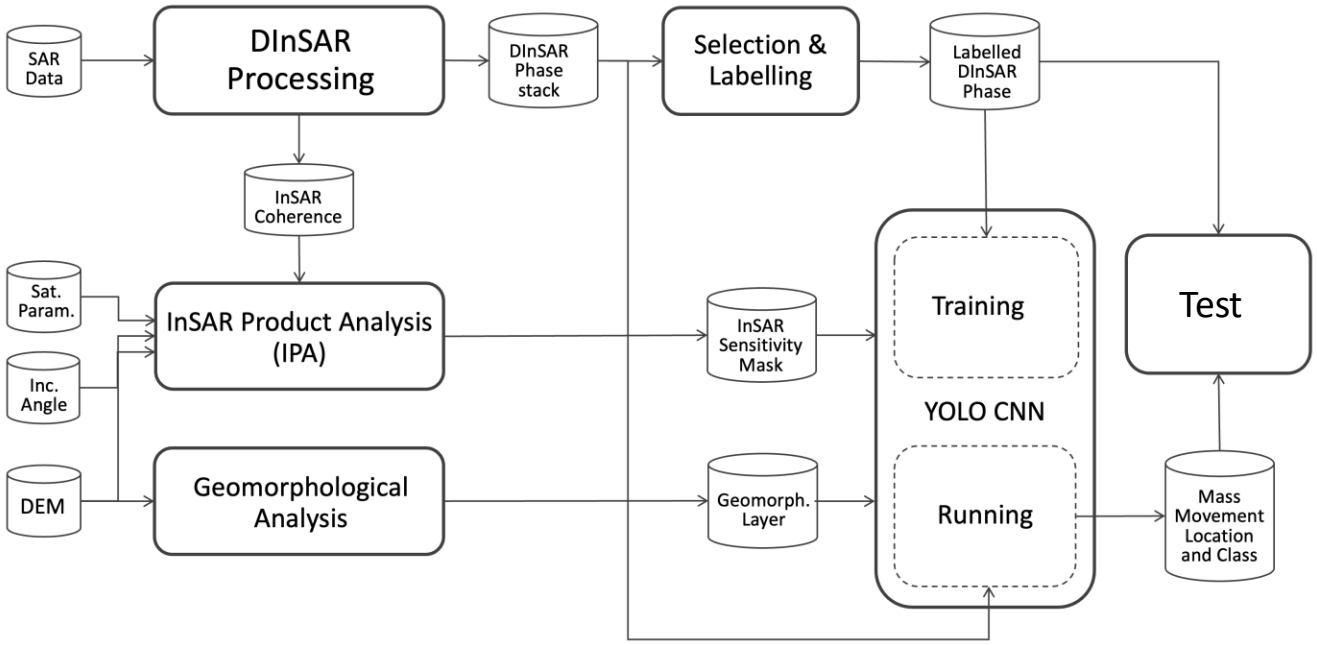
Mass movement Investigation and prediction through geomorphology, Remote sensing and Artificial intelligence

GOAL: **automatically detect** and **classify** active processes in **SAR interferograms**

CHALLENGE: exploit **full DInSAR phase** signal (**"raw" wrapped interferograms**)

→ **rapid meaningful data** to experts: classified **bounding boxes**

→ **free**, routinely **available SAR imagery**: Sentinel-1 (**C band**)



What do we need?

1 Geomorphologically-constrained **dataset** of **DInSAR signals**

2 ***Machine Learning model*** *able to* ***emulate*** ***human expert interpretation***

Deep Learning model

YOLOv3 *(Redmond and Farhadi, 2018)*

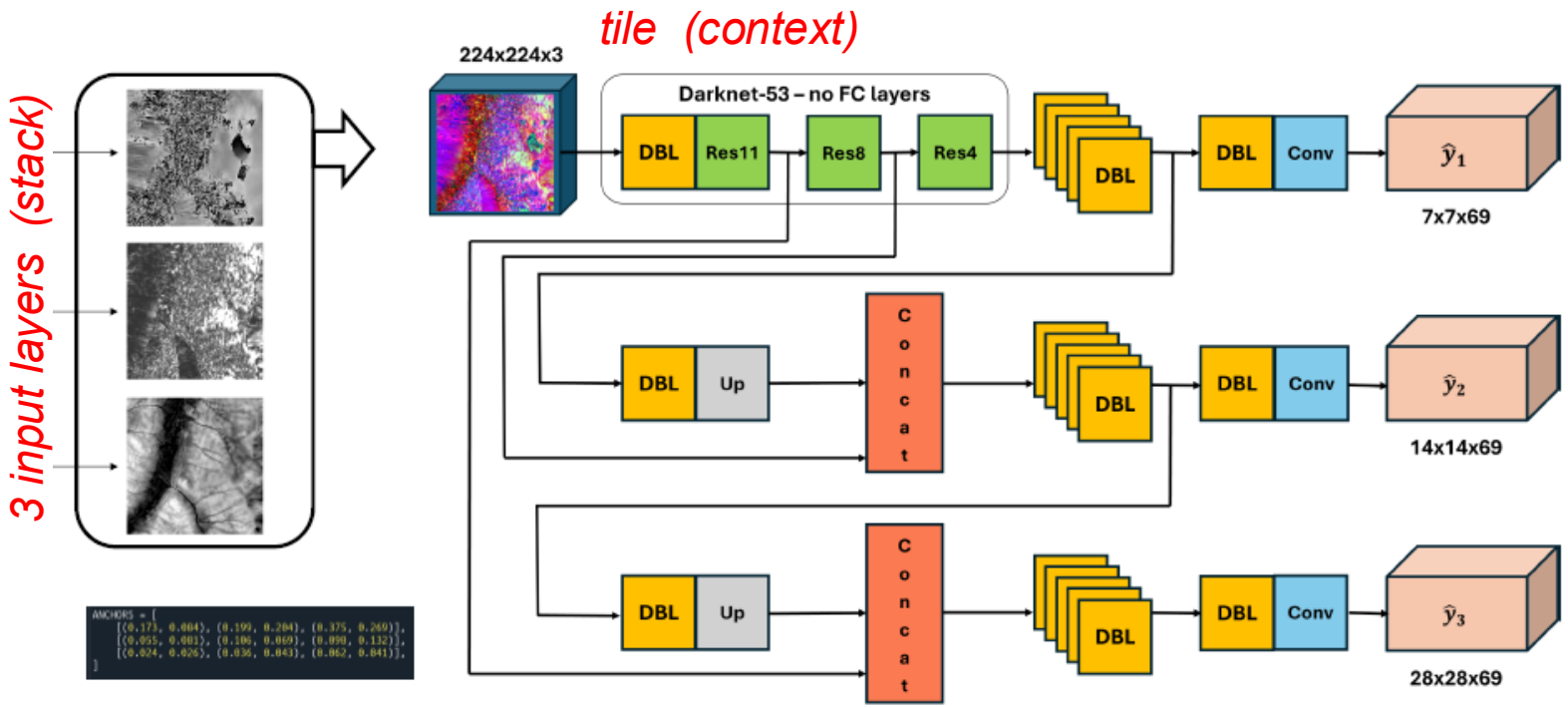
→ **real-time**, **fast** and **accurate object detector**

→ captures objects of **variable size** and **shape** within their **context**

→ does not provide object outlines but **"bounding boxes"**

CHALLENGE:

capture processes over a wide range of size and velocity



YOLO-MIRAGE CNN

3-layer (16-bit) input stack

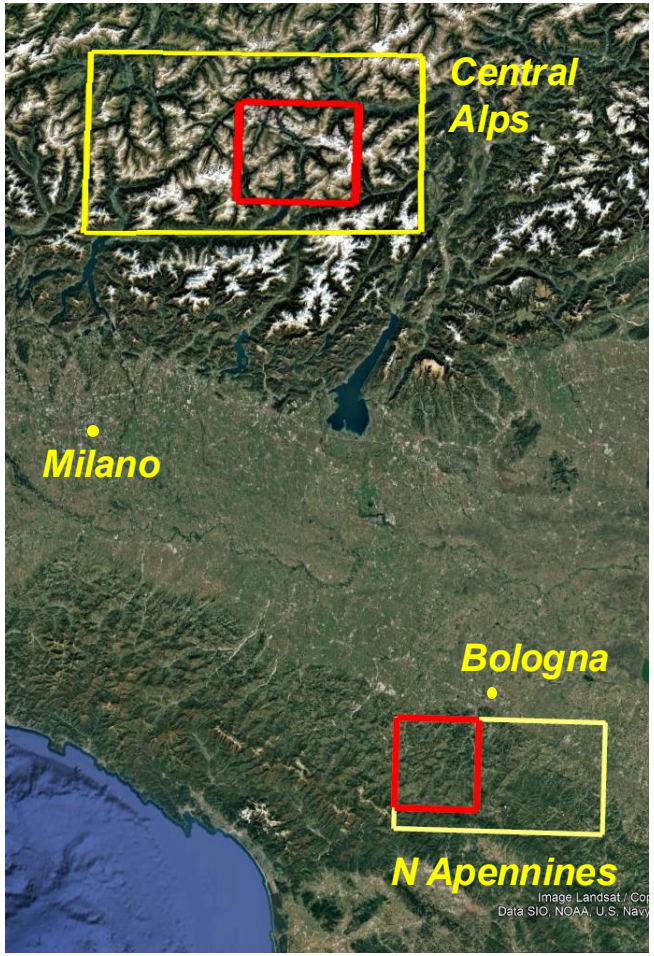
→ wrapped phase

→ InSAR sensitivity

→ geomorphometric layer

Attempt to emulate human expert interpretation

Study areas



Central Italian Alps *(Lombardia, TN, BZ, CH)*

→ *test area: 9700 km², training:* ***1900 km²***

→ *para-periglacial environment*

→ *metamorphics, minor granitoids and carbonates*

DSGSD (**DG**), rockslides (**RS**), debris slides (**DS**), rock glaciers (**RG**), protalus r. (**PR**), talus (**TA**)

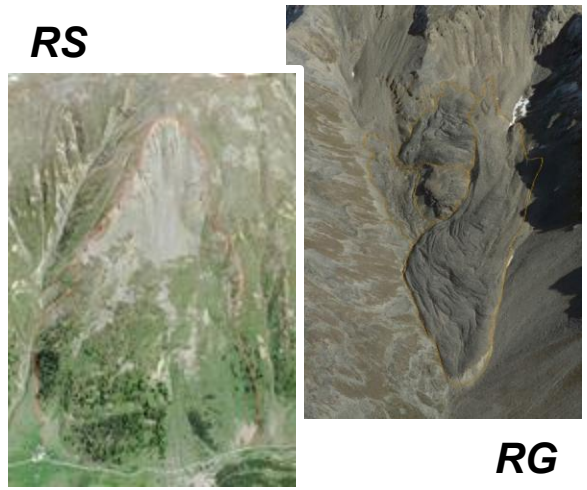
N Apennines (Emilia-Romagna):

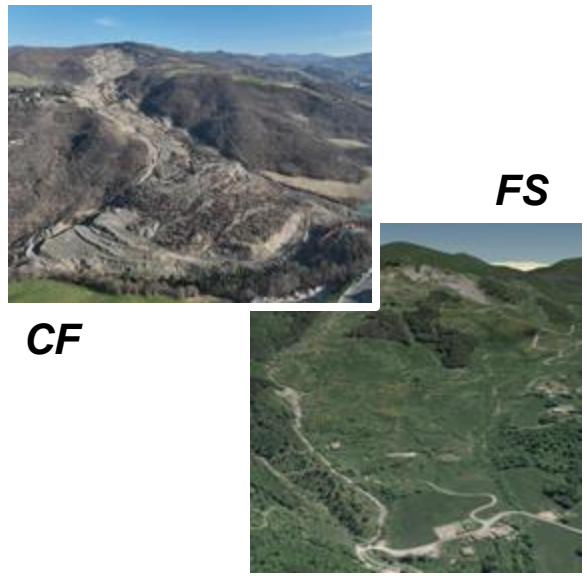
→ *test area: 3400 km², training:* ***1150 km²***

→ *fluvial-dominated environment*

→ *clay-shales, flysch, sandstones*

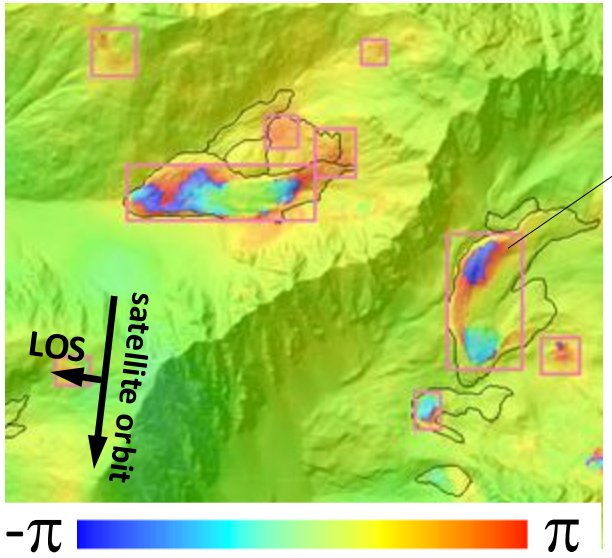
earthflows (**CF**), earthslides in clay-shales (**CS**), or flysch (**FS**)





Different environments, very different mass movement processes and sizes !

YOLO-MIRAGE layers: DInSAR wrapped phase

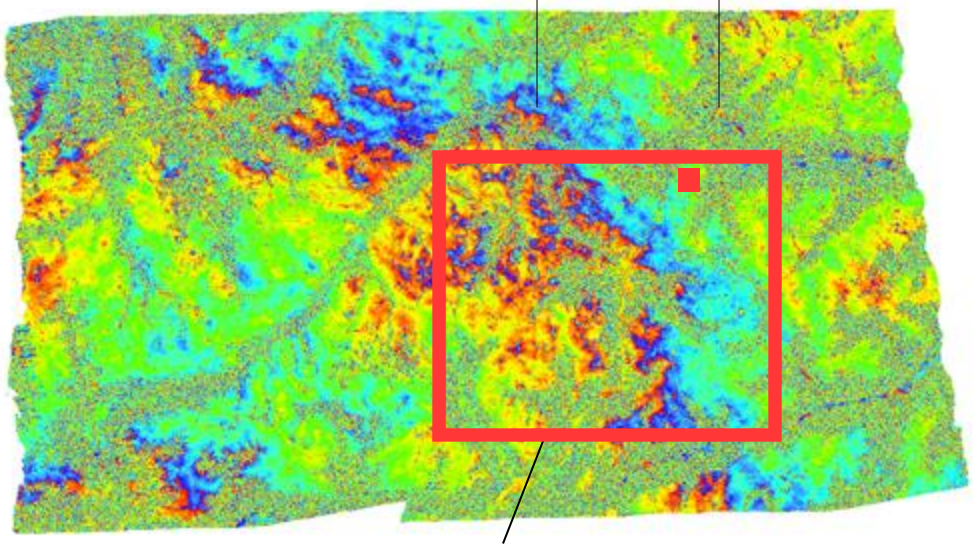


Fringes (modulo 2π)

APS

decorrelation

Signals



Test area (9700 km²)

e.g. Bt =12d

Training area (1900 km²)

Wide-area DInSAR processing *(Sentinel-1, **C band**)*

→ ascending and descending orbits

→ different **temporal baselines** (Bt: **6 to 365 days**)

→ **filtered IFG**, **no unwrapping**, **no APS correction**

→ geocoded in EPSG: 32632; sampling on DEM (**15 m**)

Products: **wrapped phase**, **coherence**

Alps

→ *2019-2021: 300 processed IFG (119 ASC, 181 DESC)*

→ *Bt: 6, 12, 30, 60, 90, 365 days*

Apennines

→ *2015-2025: 1042 processed IFG (585 ASC, 457 DESC)*

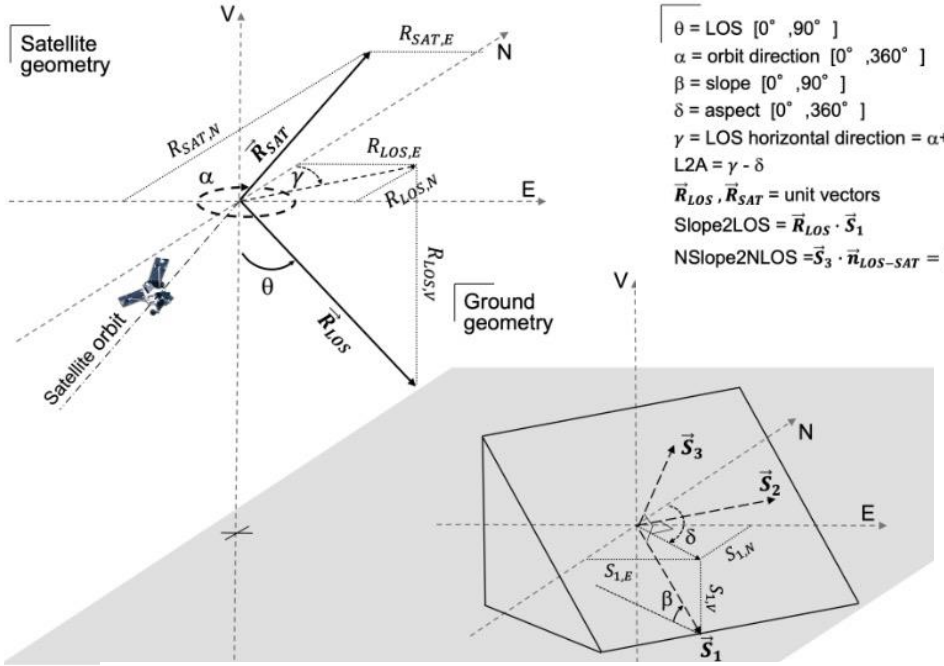
→ *Bt: 6, 12, 18, 24, 30, 36 days*

YOLO-MIRAGE layers: InSAR sensitivity

InSAR Sensitivity Mask - ISM *(Bovenga and Piccolino, 2025)*

→ **reliability** of the **information** content of InSAR **phase** in input to machine learning

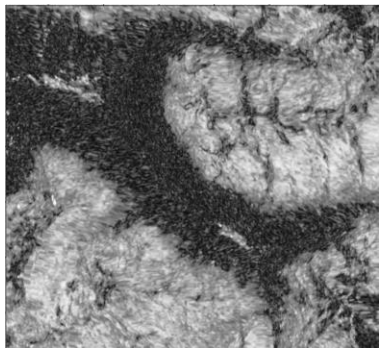
→ combines **geometric InSAR sensitivity** to downslope movement (**S2L**) and **coherence** (weighted)



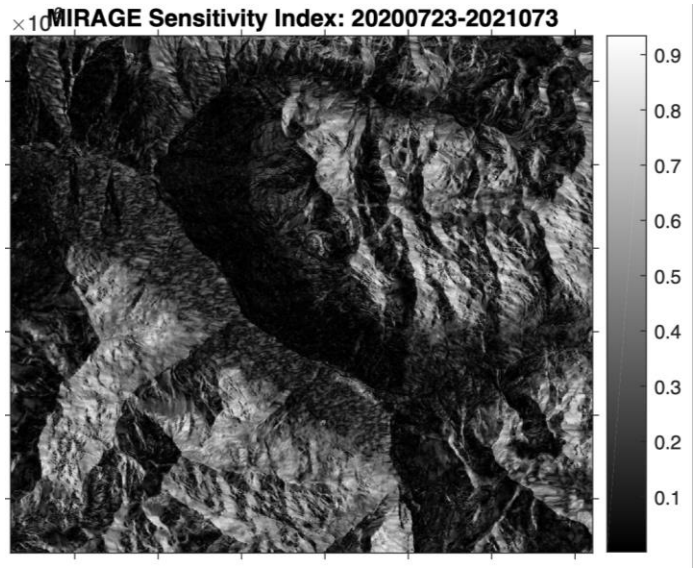
θ = LOS [0° ,90°]
α = orbit direction [0° ,360°]
β = slope [0° ,90°]
δ = aspect [0° ,360°]
γ = LOS horizontal direction = α+90°
L2A = γ - δ
$\vec{R}_{LOS}$, $\vec{R}_{SAT}$ = unit vectors
Slope2LOS = $\vec{R}_{LOS} \cdot \vec{S}_1$
NSlope2NLOS = $\vec{S}_3 \cdot \vec{n}_{LOS-SAT} = (\vec{S}_1 \times \vec{S}_2) \cdot (\vec{R}_{LOS} \times \vec{R}_{SAT})$

$$W(x,y) = |S2L(x,y)| \cdot \left(W_{Coh}(x,y) \cdot \gamma(x,y)\right)$$

Geometry (ISL)



weighted coherence

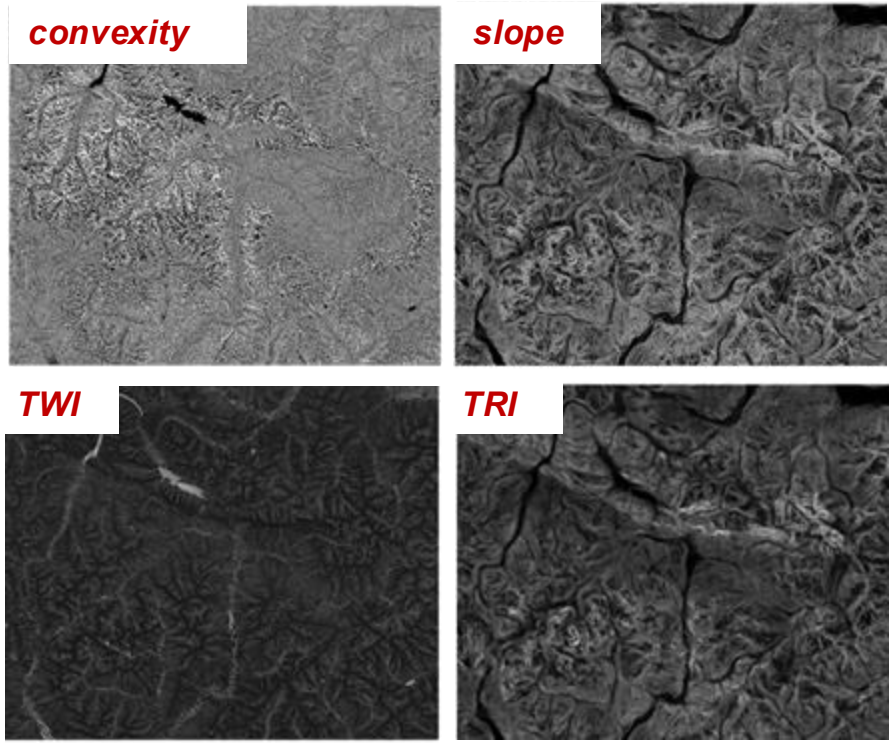


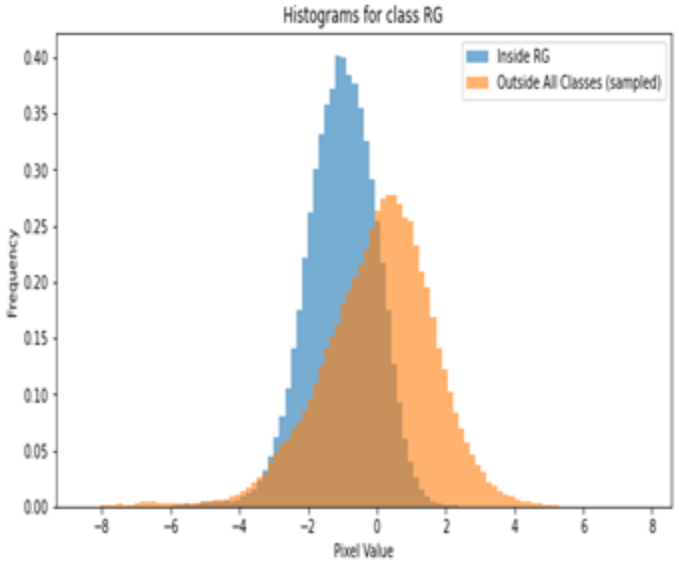
Study Area 1 (Italian Northen Alps)
Sentinel-1
Orbit Pass Mode: ASC
Sat. Height: 693 km
Inclination Angle (deg): 98.18°
Incident Angle (deg): 43.4°

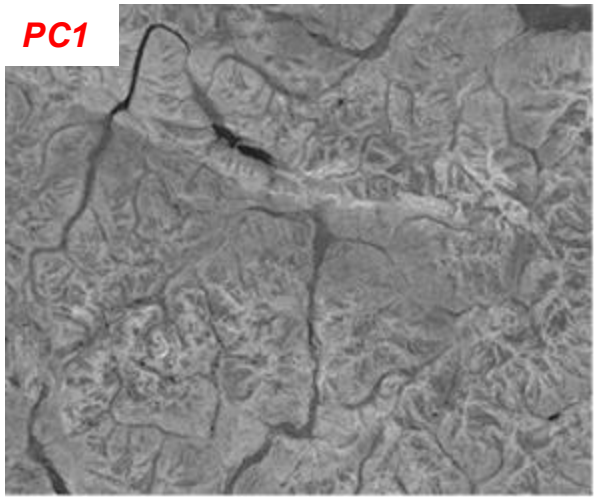
YOLO-MIRAGE layers: geomorphometry

Principal Component Analysis (PCA) on morphometric variables

- → landscape **morphometric signatures**: DEM-derived products
- → **variables**: slope, convexity, Terrain Roughness Index (TRI) and Topographic Wetness Index (TWI)
- → Principal Component Analysis (**PCA**): **synthesize** different **discriminant variables**







PC1 shows the greatest ability to discriminate between inner and outer slope processes and between different types of processes.

Library of DInSAR wrapped phase signals

→ map **DInSAR phase signals** of **active processes**: **bounding box (BB)**

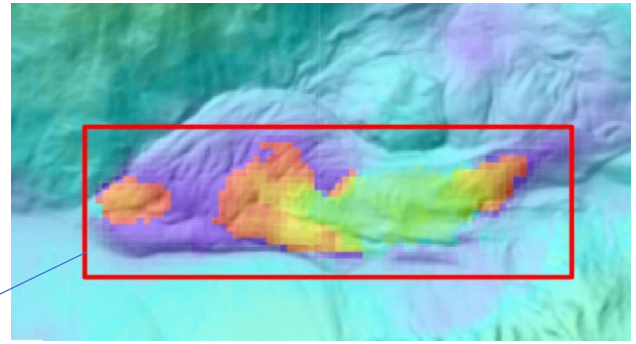
→ ancillary supporting **datasets** (DEM, ortophotos, **inventories**)

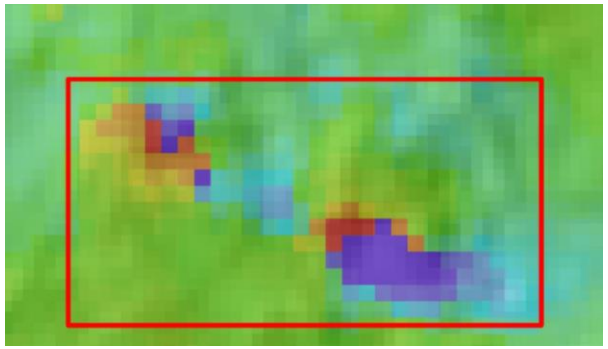
Reyes-Carmona et al. (2026)

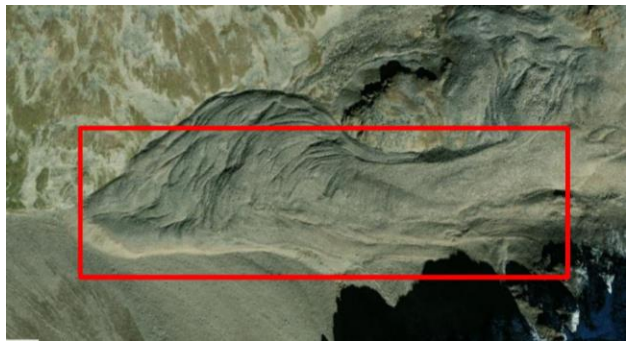
DInSAR wrapped phase signal

Bounding Box

Process







rock glacier (RG), Bt: 12d

Earthflow (CF), Bt: 12d

LABEL

=

Bounding box

+

Interferogram patch

+

attributes
(class, Bt, etc)

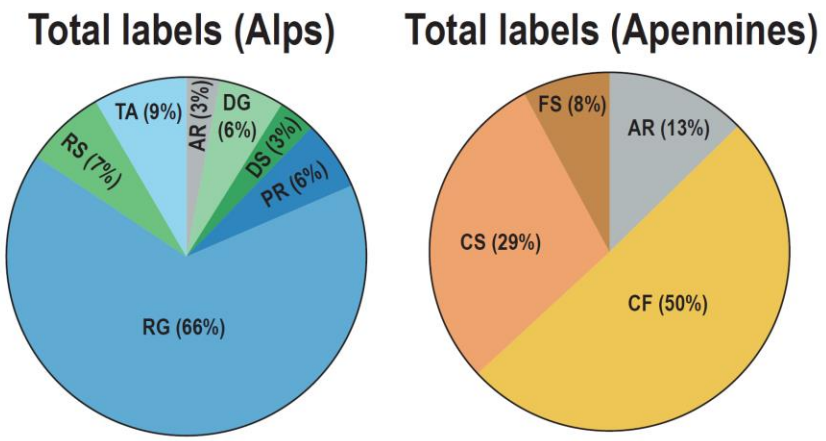
Strongly geomorphologically-constrained labeling (→ model training / interpretation)

Library of DInSAR wrapped phase signals

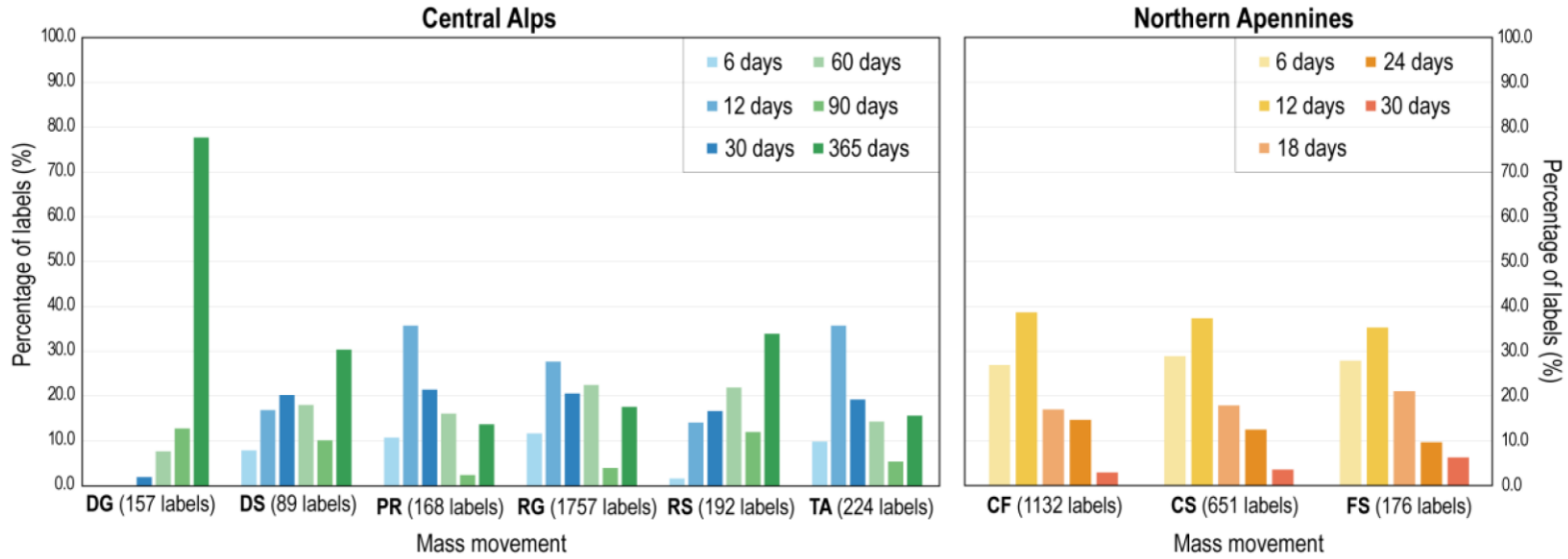
Mass movement class	N° labels	% of total labels	Mean area (km²)	Main baseline (days)	Phase signal pattern (shape, texture)
Artifact (AR)	80	3.0	0.11	-	-
Deep-seated deformation (DG)	157	5.9	0.65	365	Broad, homogeneous
Debris slide (DS)	89	3.3	0.10	365	Localised, heterogeneous
Protalus rampart (PR)	168	6.3	0.04	12	Elongated, heterogeneous
Rock glacier (RG)	1757	65.9	0.04	12	Elongated, homogeneous
Rockslide (RS)	192	7.2	0.13	365	Localised, homogeneous
Talus (TA)	224	8.4	0.05	12	Elongated, heterogeneous
Total Central Alps	**2667**				
Artifact (AR)	284	12.7	0.08	-	-
Earthflow in clay-shales (CF)	1132	50.5	0.06	12	Elongated, homogeneous
Earthslide in clay-shales (CS)	651	29.0	0.06	12	Localised, homogeneous
Rockslide in flysch rocks (FS)	176	7.8	0.07	12	Localised, homogeneous
Total Northern Apennines	**2243**				

Reyes-Carmona et al. (2026)

- → **4910** labels (Alps: 2667; Apennines: 2243)
- → repeated detections (Alps: 550; Apennines: 233)
- → process **classes** (Alps: 7 cl.; Apennines: 4 cl.)
- → **temporal baseline** dependence



class imbalances

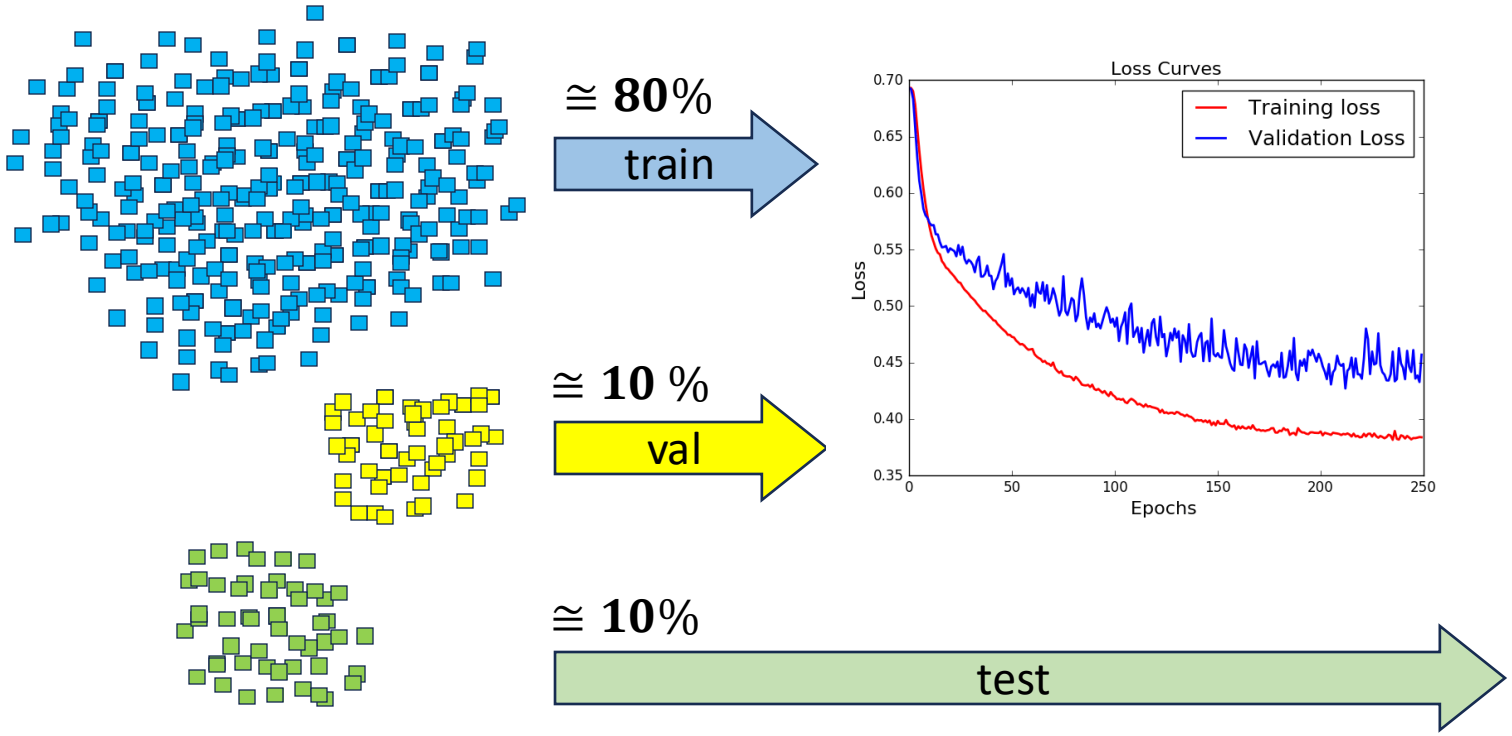


Model training/validation and testing

- → **input tiles**: 160x160 (Apennines), 224x224 (Alps)
- → **anchor boxes**: k-means clustering of **mapped bounding boxes**
- → data **augmentation**
- → dataset **splitting: traning/validation** (80/10) and **testing** (10)

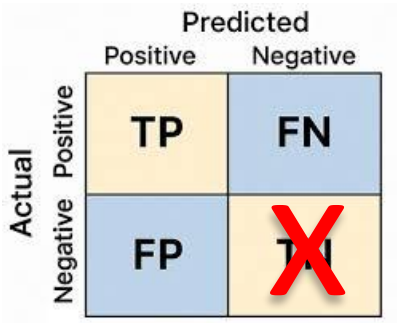
3 predictions

1) *object occurrence*
2) *bounding box*
3) *class*



Metrics

- → Precision, Recall, F1-score, mAP
- → TP: based on **IoU threshold (0.5)**



True negatives excluded!

(imbalance)

YOLO-MIRAGE performance

N Apennines:

→ precision: 0.63

→ recall: 0.93

→ mAP: **0.883**

→ global F1-score: **0.751**

Performance: excellent

Central Alps:

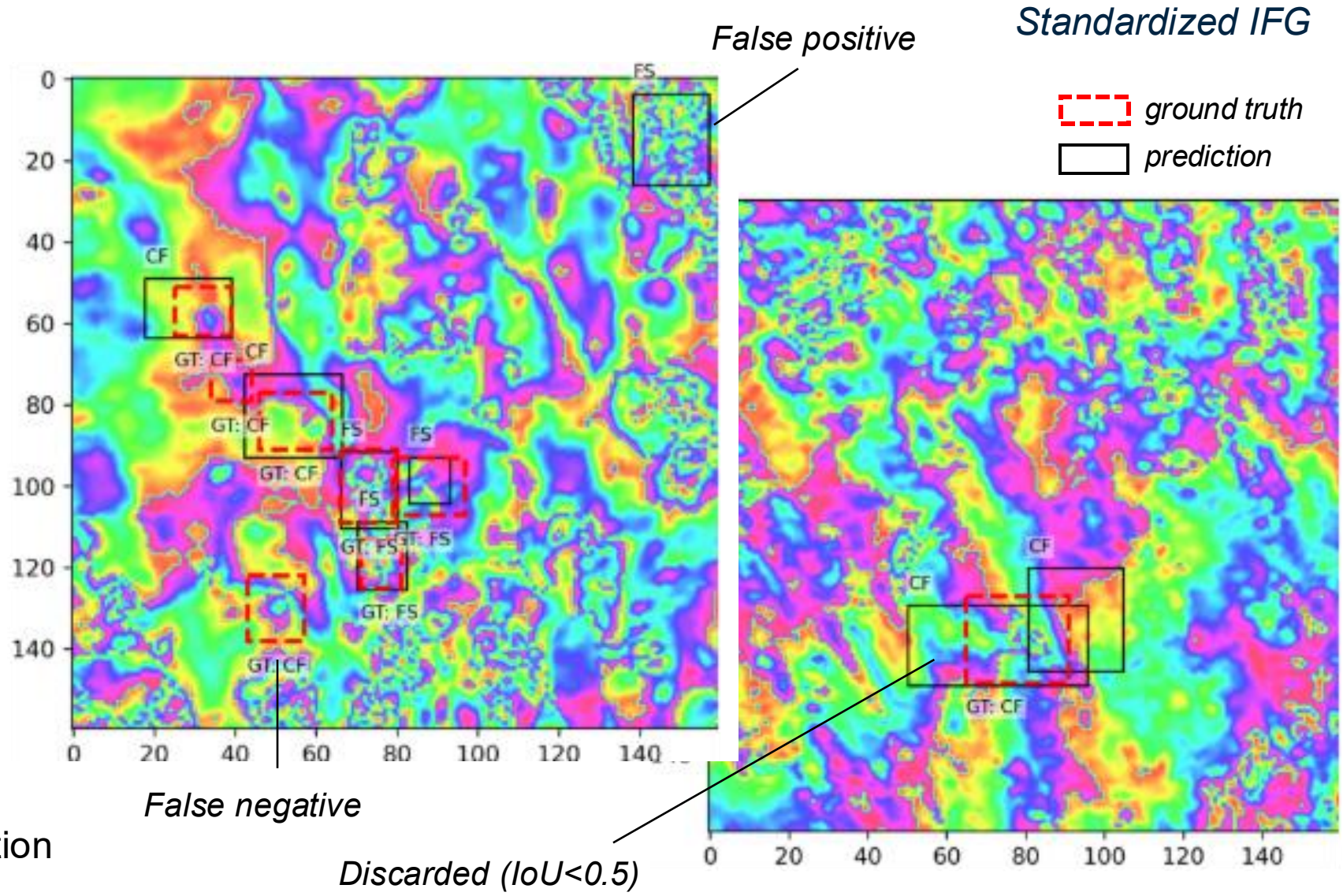
→ precision: 0.69

→ recall: 0.75

→ AP: **0.765**

→ global F1-score: **0.717**

Performance: poor in classification



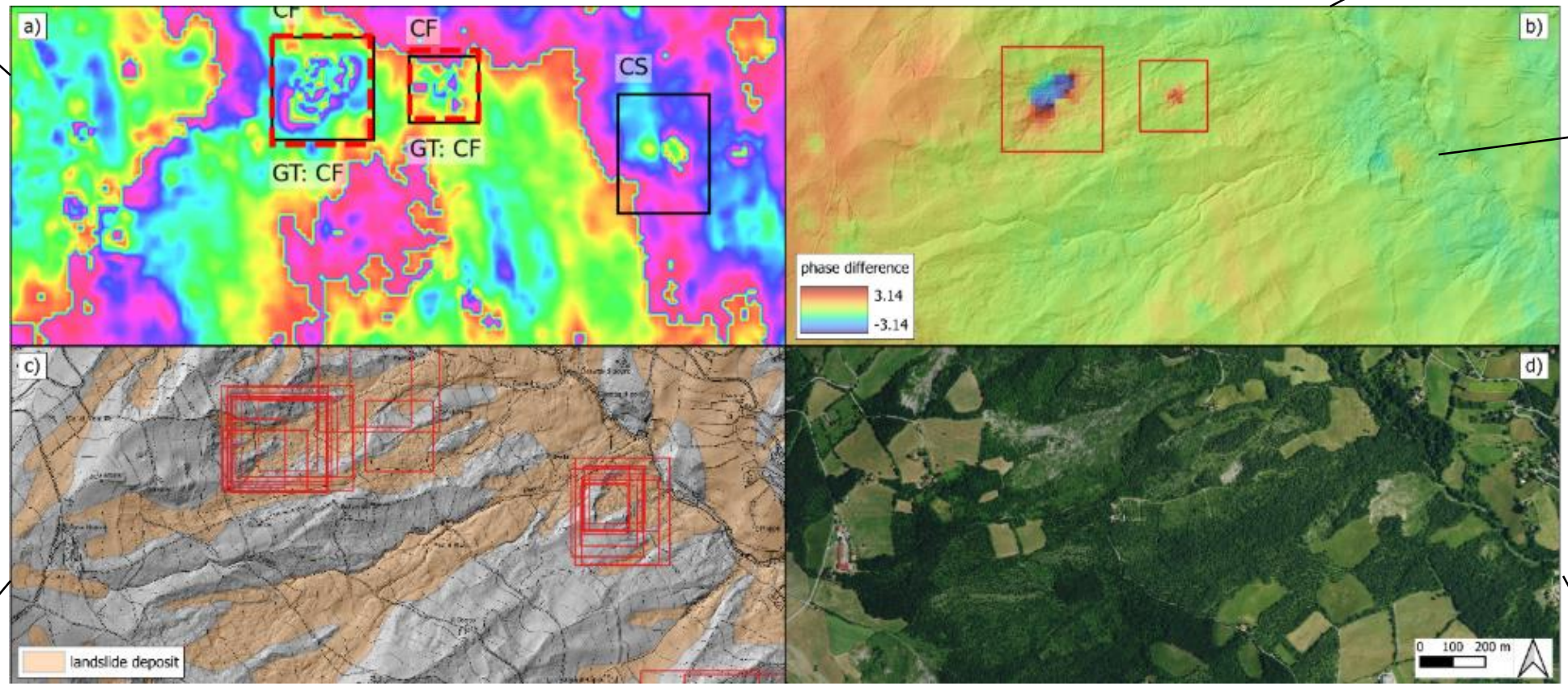
Human emulation: geomorphological evaluation

N Apennines: *earthflows (CF) and earthslide (CS)*

Mapped bounding boxes on IFG

Prediction

Ascending 12 days: 01/03/2017 – 07/03/2017



?

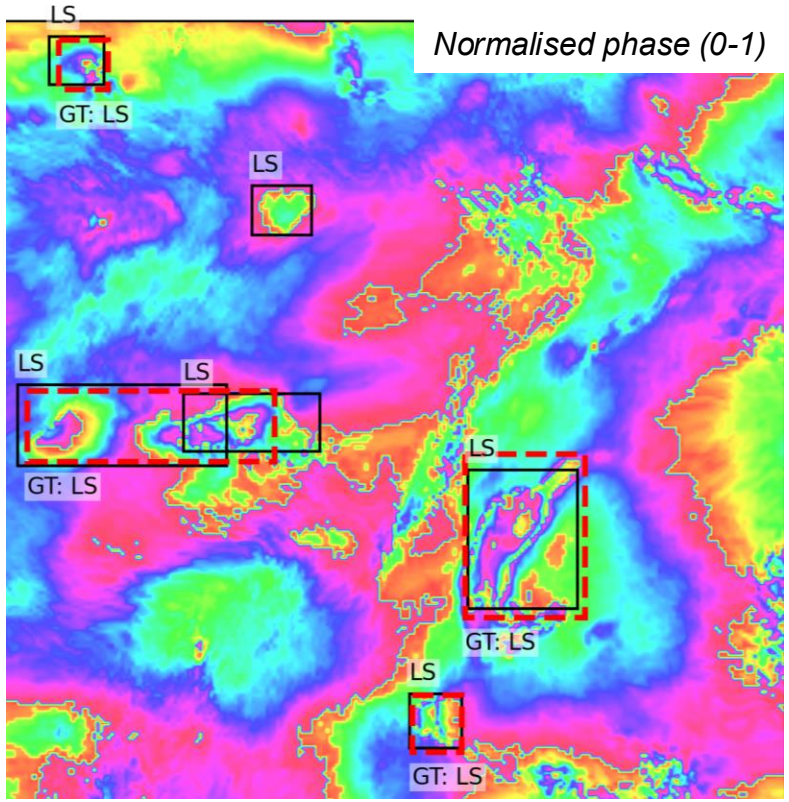
Mapped signals on multiple IFGs

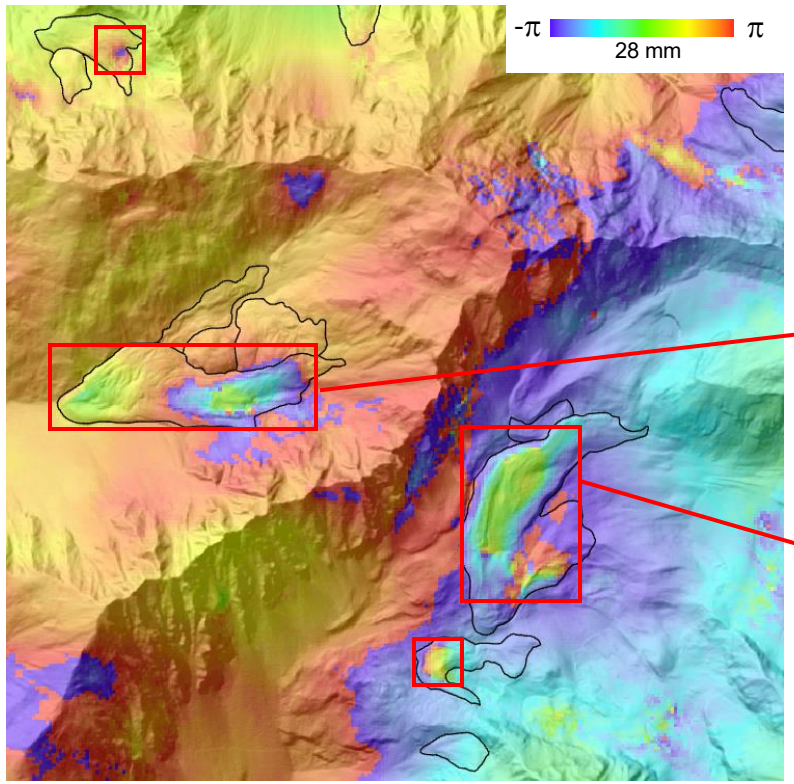
Orthophoto

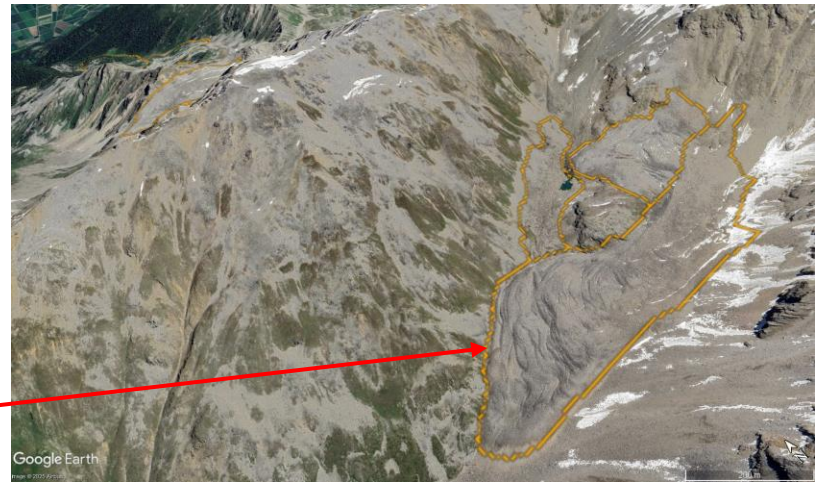
Human emulation: geomorphological evaluation

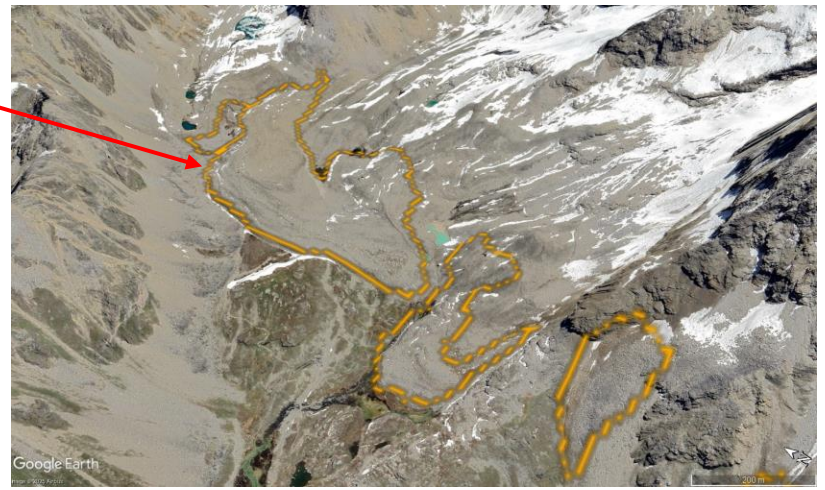
Central Alps: *periglacial landforms (rock glaciers)*

Ascending 12 days: 04/09/2020 – 16/09/2020









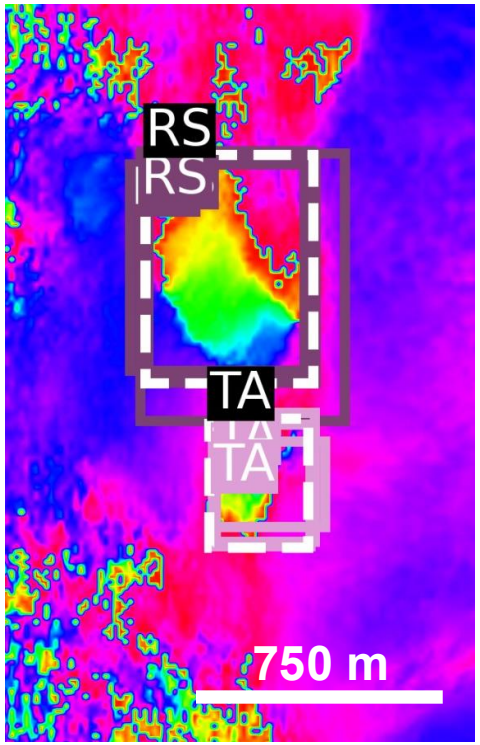
ground truth

prediction

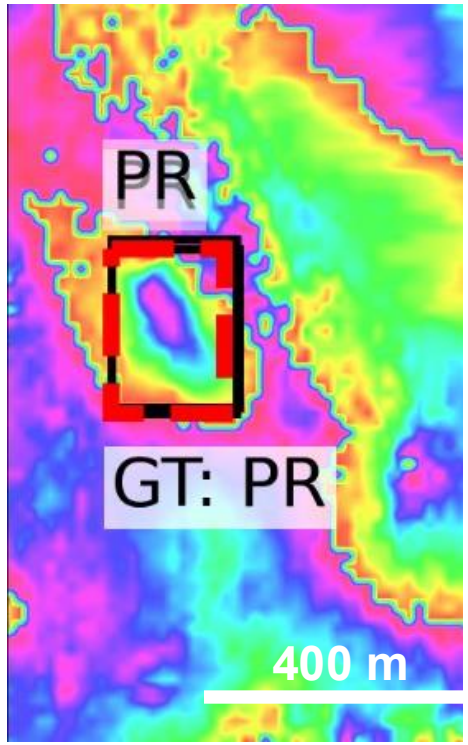
Rock glacier **Label**

Human emulation: process interpretation

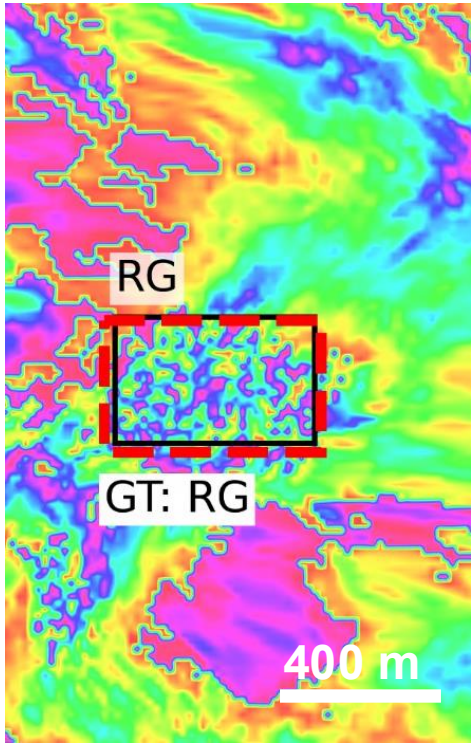
Process-oriented evaluation of **detected fringe patterns**



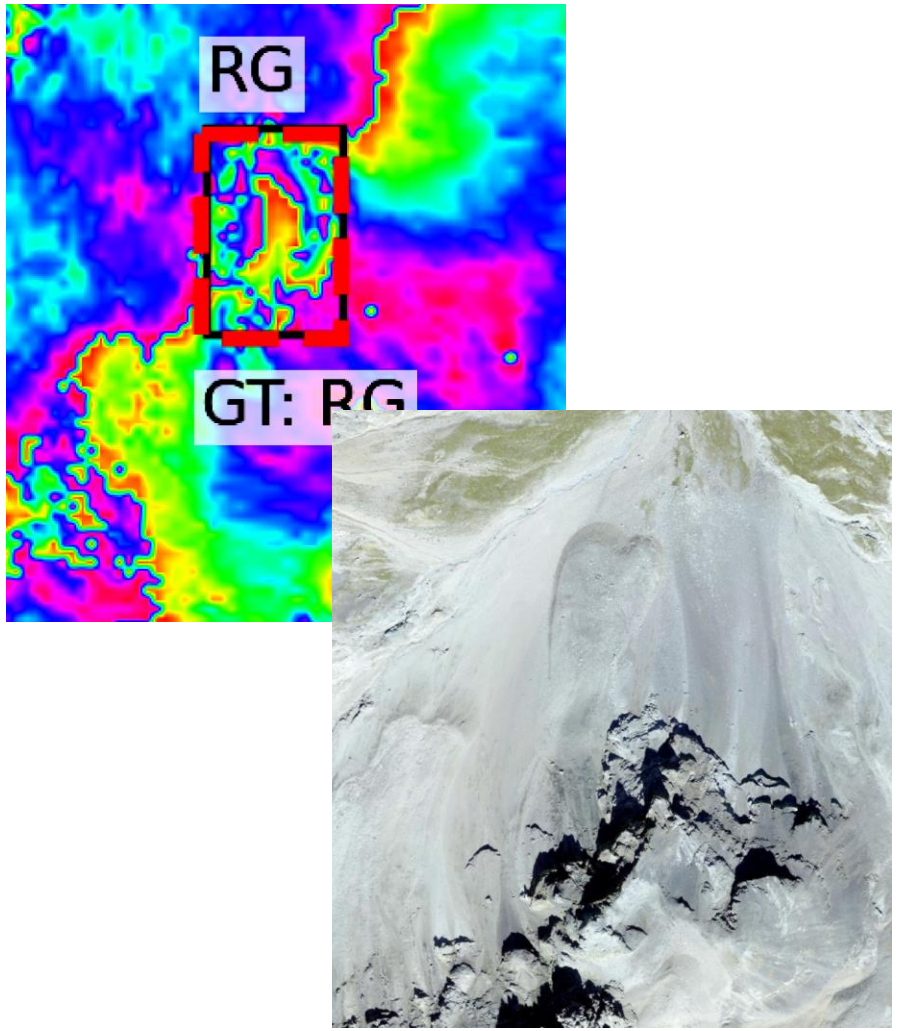
Rockslide TP
(clear fringes)



Rock glacier TP
(clear fringes)



Rock glacier TP
(in decorrelating area!)



Prediction vs field data: interpretation

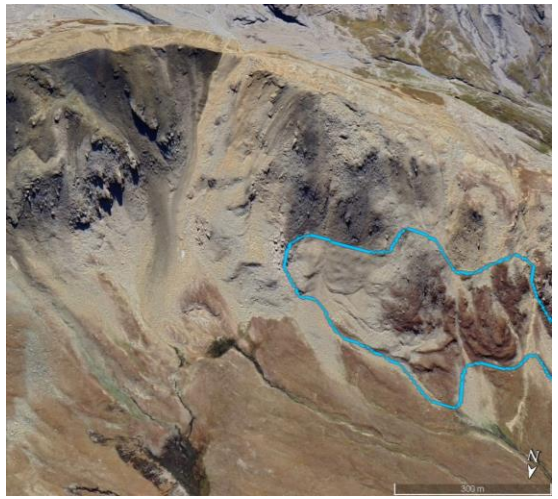
“Apparent” false positives: see better than human?

Expert-annotated database **incompleteness** *(mass movements are not cats!)*

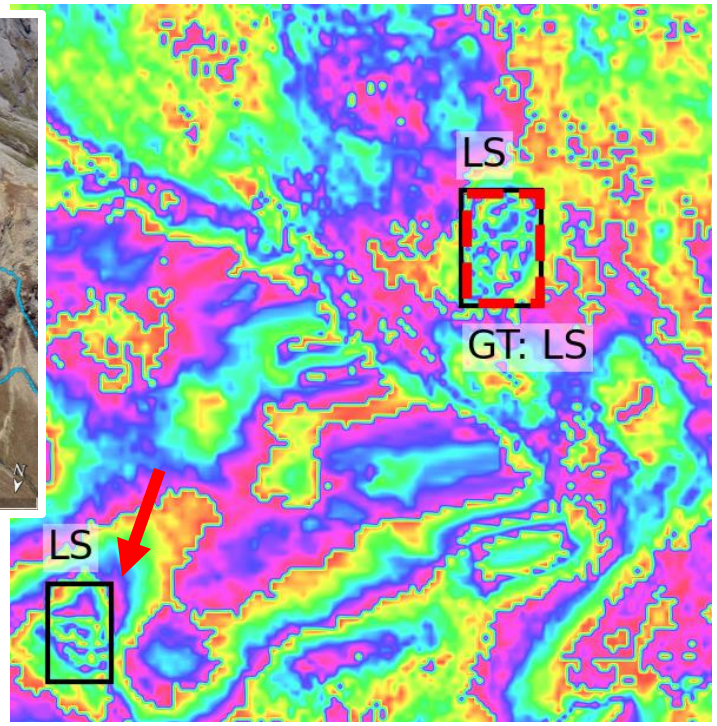
→ an interferogram is 16-bit deep, a PC screen 8-bit, human eye sees 4-5 bit !

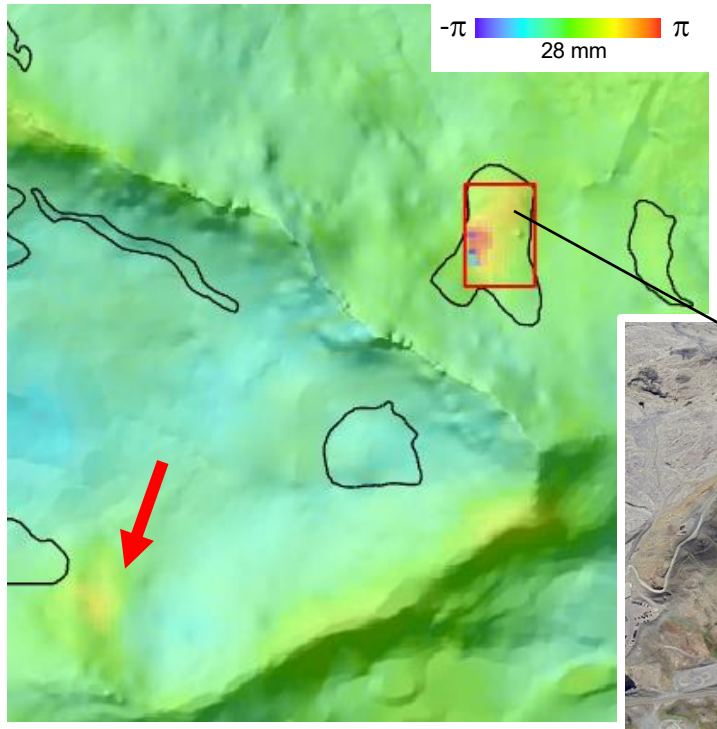
→ small or low SNR signals can be overlooked

Ascending 12 days: 18/08/2021 – 30/08/2021



False positive?
Actually a true positive!





ground truth
prediction

Rock glaciers

Geomorphological validation → dataset **update** → AI model **refinement**

Take-home messages

AI for active mass movement mapping: <u>challenges</u>

→ many types, **sizes** and **rates**

→ need to fully exploit the information of **raw InSAR data**

MIRAGE: novel dataset + model to unlock the **potential** of routinely available InSAR products

→ intercept **mass movement signals** in **InSAR wrapped phase**

→ **multiple spatial** and **temporal scales**

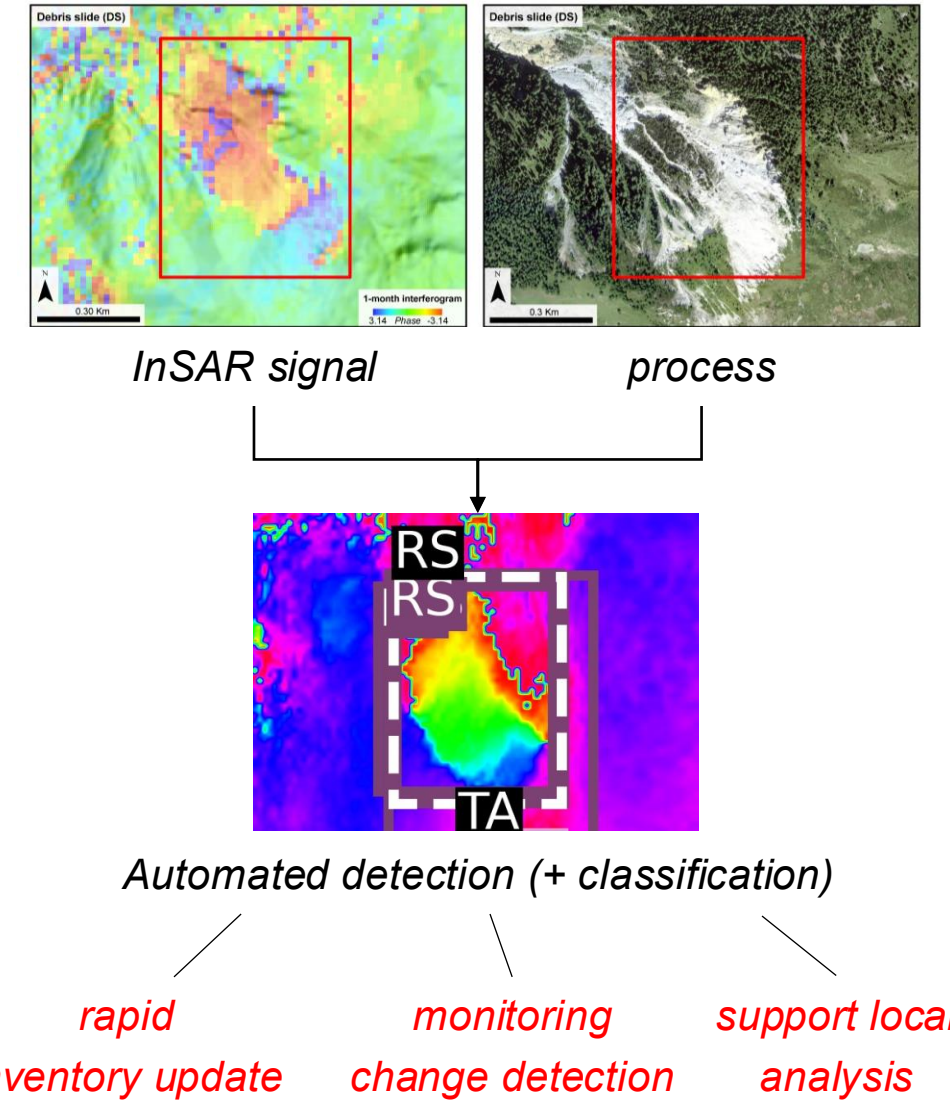
→ **detect** and **classify** (in certain conditions)

→ **geomorphologically-constrained / interpretable**

Open issues

→ **classification**: exceeding expectation OR difficult (eg. Alps)

→ **generalization** (processes, environments, InSAR products)



Thank you!!

→ EU-Next Generation EU, Mission 4, Component 2, CUP H53D23001660006: PRIN22 **MIRAGE** project (Mass movement Investigation and prediction through geomorphology, Remote sensing and Artificial intelligence)

→ ESA's EO Science for Society component of the FutureEO-1 Segment 2 Programme (grant no. 4000143903/24/I-DT-bgh): **MODULATE** project (MOnitoring lanDslides with mUltiplatform L-Band rAdar Techniques)