Image source: https://www.nationalgeographic.fr/voyage/krizna-la-sublime-grotte-slovene-sculptee-par-les-eaux - Krizna cave in Slovenia

Karst aquifers are widespread

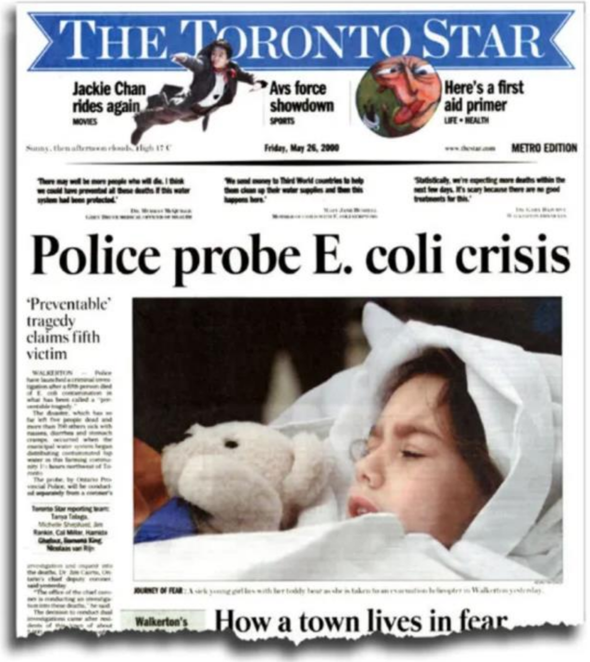
Karstifiable rocks (potential karst aquifer)

- *Continuous carbonate rocks*
- *Discontinuous carbonate rocks*
- *Continuous evaporite rocks*
- *Discontinuous evaporite rocks*
- *Mixed carbonate and evaporite rocks*

Freshwater for 25% of world population

Loue spring in the Jura, https://www.destinationlouelison.com/decouvrir/les-vallees-de-la-loue-et-du-lison/la-source-de-la-loue/

Water pollution
in Walkerton, Canada


THE TORONTO STAR

Jackie Chan rides again

Avs force showdown

Here's a first aid primer

Friday, May 26, 2000

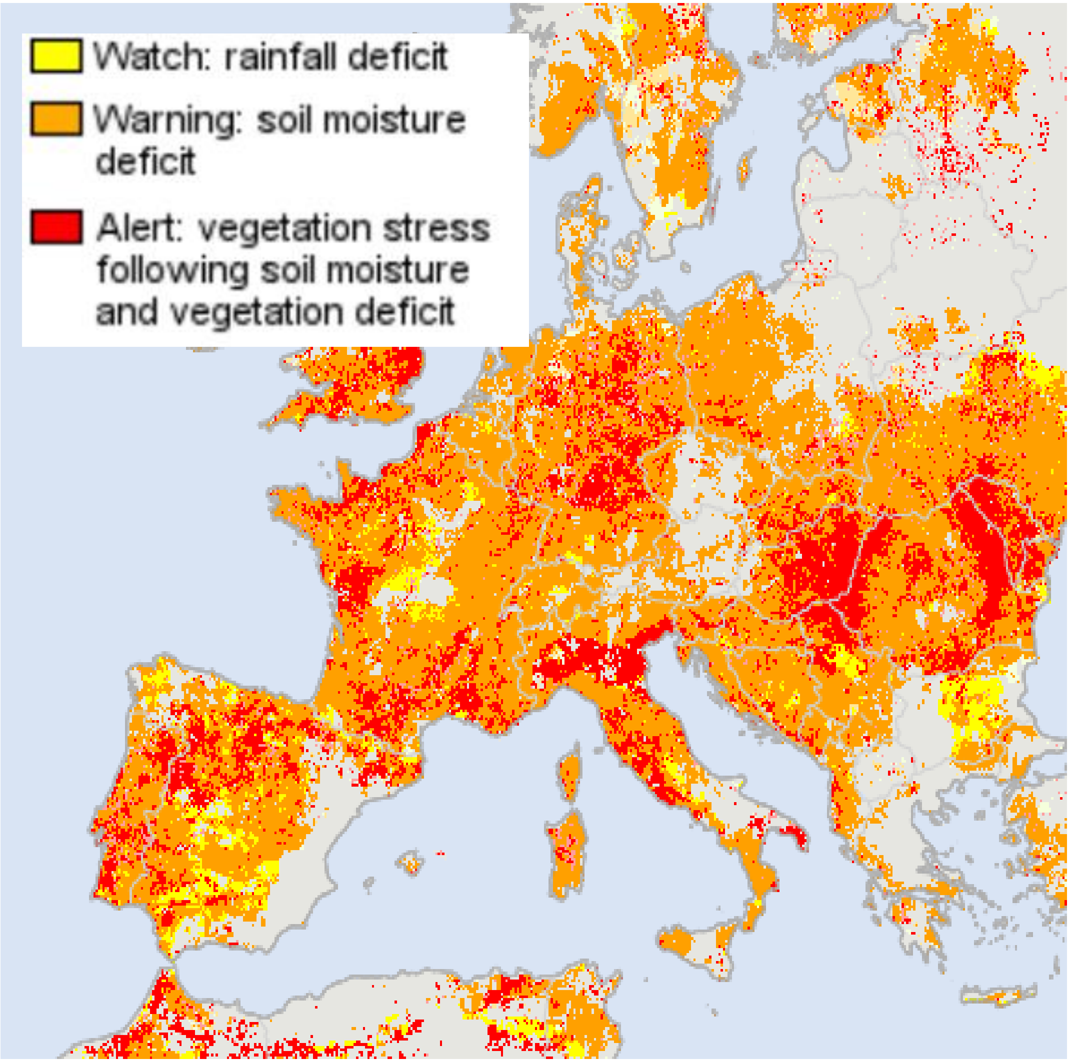
METRO EDITION

Police probe E. coli crisis

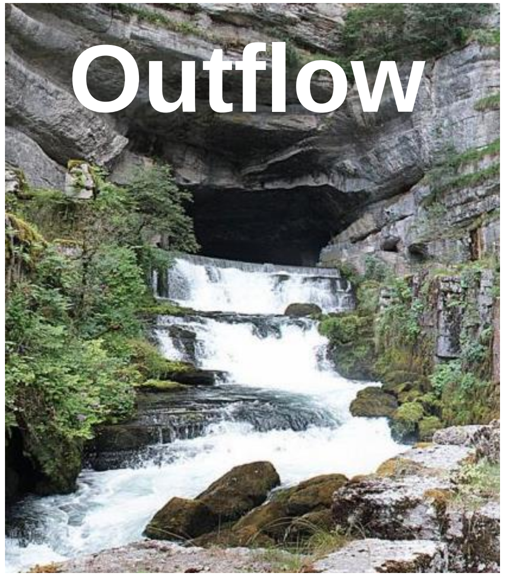
'Preventable' tragedy claims fifth victim

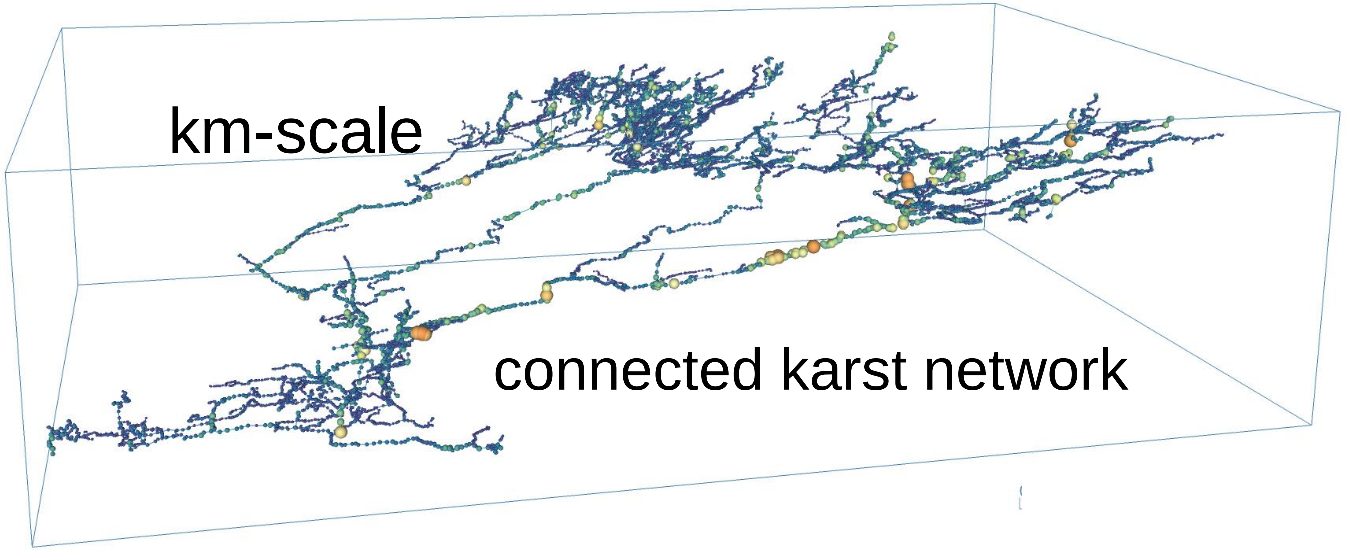
How a town lives in fear

Drought indicator - Summer 2022



Karst: the scientific challenge

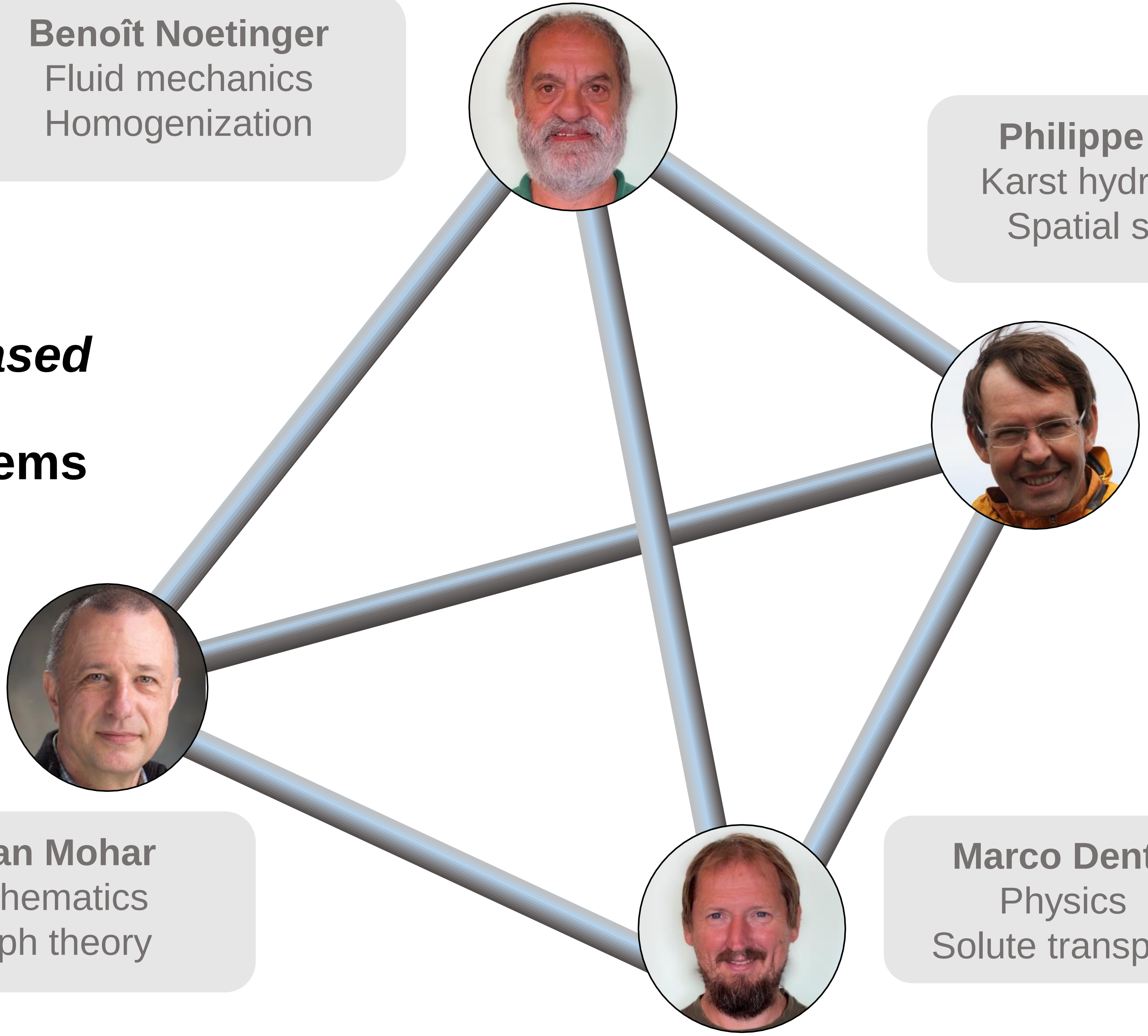




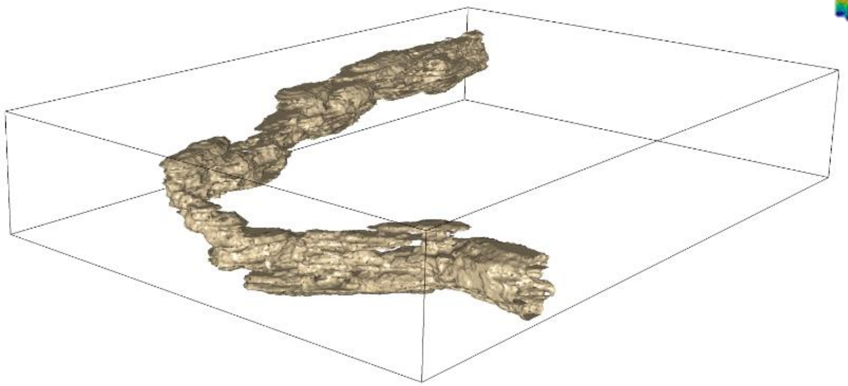
Left: Loue Spring (Jura, France) - Right: Sieben Hengste network (Swiss Alps) mapped by speleologists, and photograph of upper catchment.

Synergy of new ideas

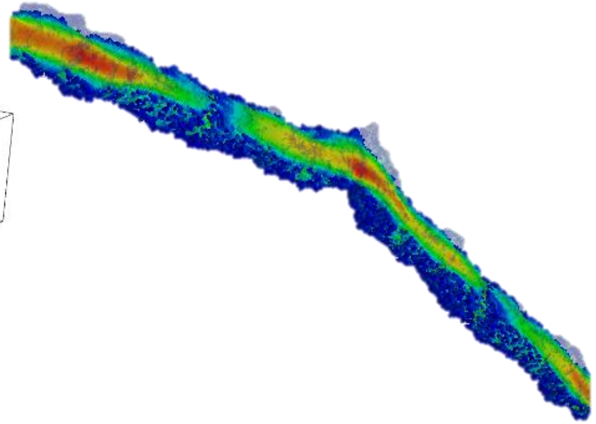
KARST Goal: *physics-based multiscale* modeling framework for karst systems



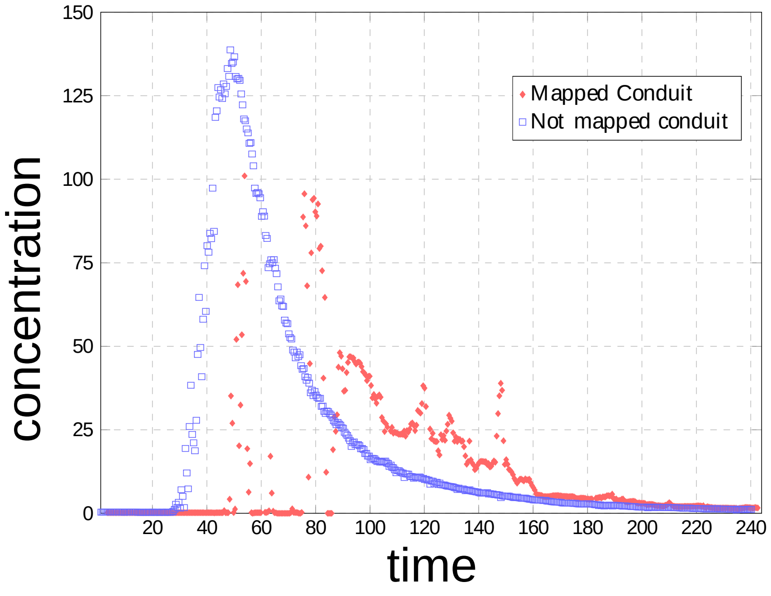
Conduit scale challenge



conduit geometry



water flow

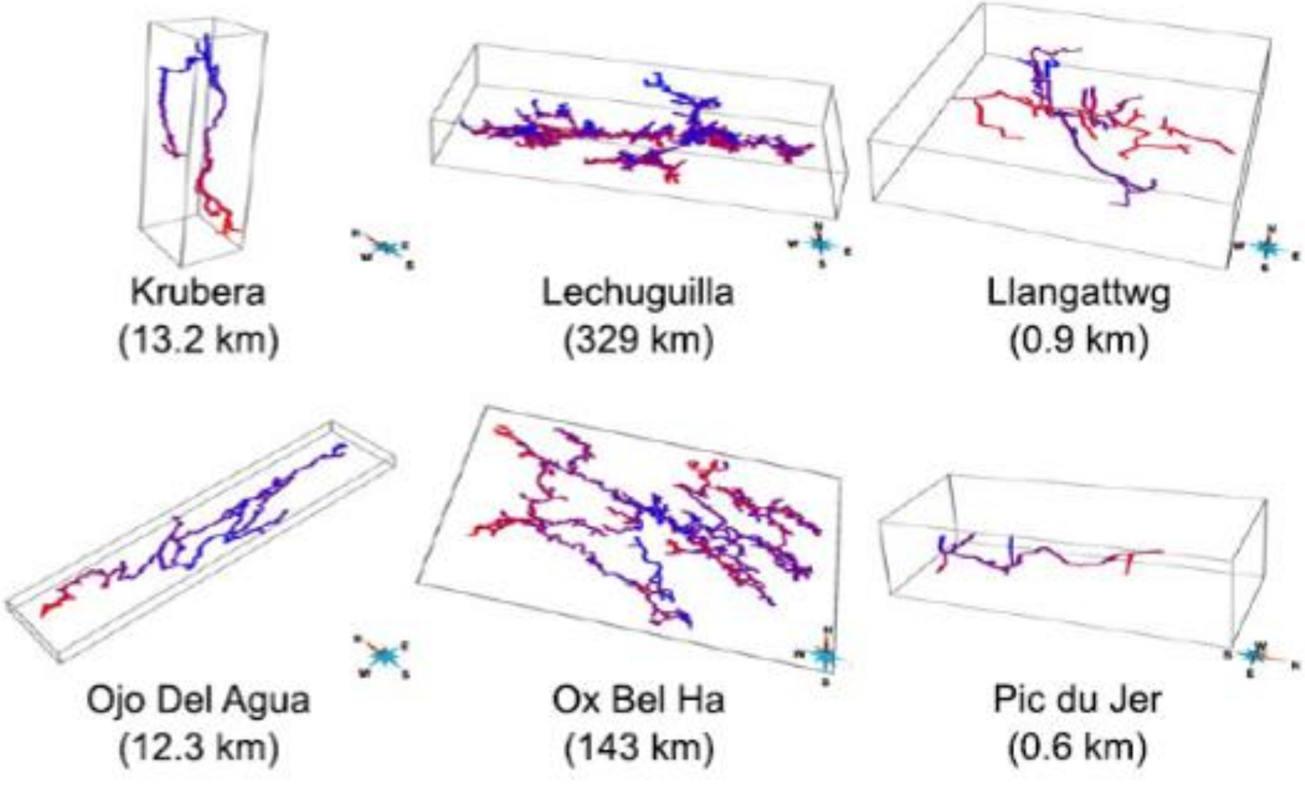


pollutant transport

Relation conduit geometry and water flow and pollutant transport is elusive

Objective 1: Establish the physics of conduit scale water flow and pollutant transport

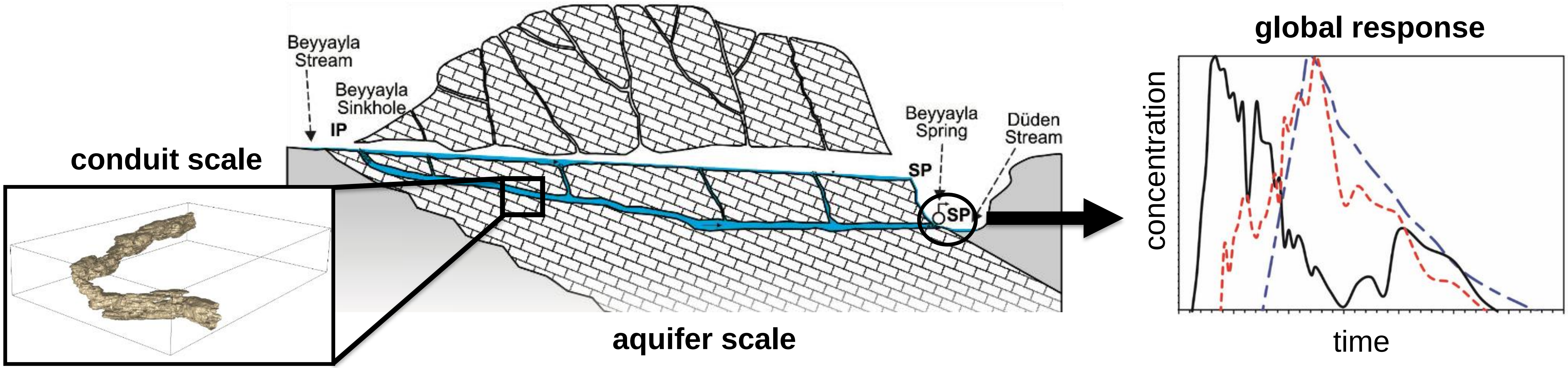
Network structure challenge



Different types of networks but no theory to classify and simulate them all.

Objective 2: Theoretical framework to simulate the structure of karst systems

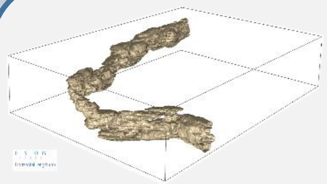
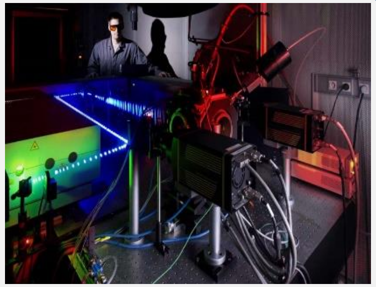
Upscaling challenge



How to integrate **conduit scale physics** and **network structure** in predictive large scale karst models?

Objective 3: Develop methods and theories to predict flow and contaminant transport processes across scales

Image modified from Aydin et al. (2014)

WP1

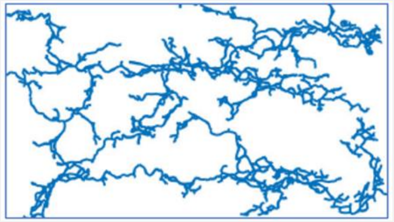
Physical laws at conduit scale

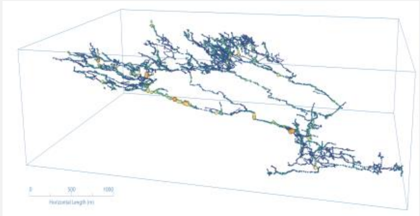
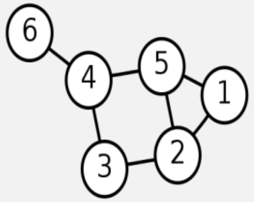
WP3

Physical laws at network scale

WP4

Modeling and forecasting
- Floods
- Contamination
- Karst formation



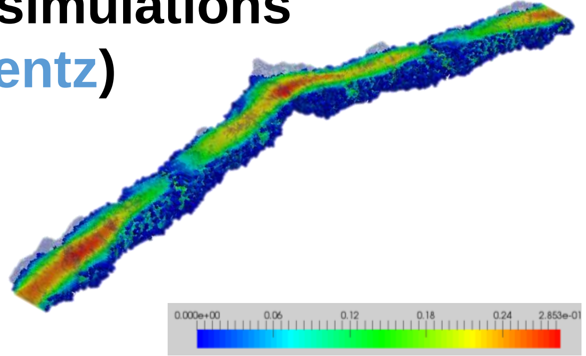



WP2

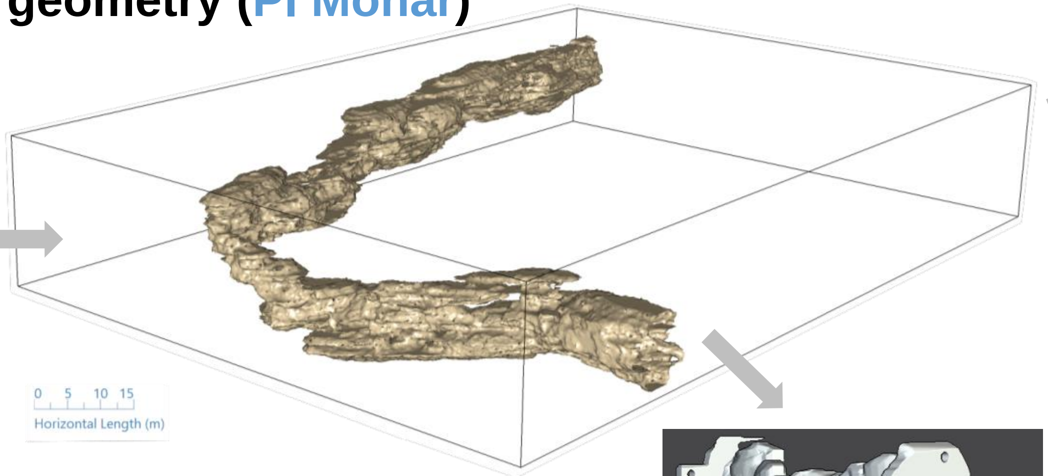
Karst network structure

WP1: Physical laws at conduit scale

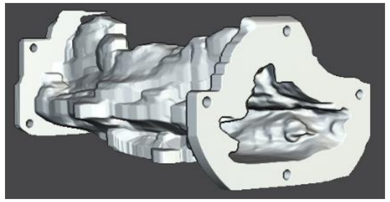
CFD simulations (PI Dentz)



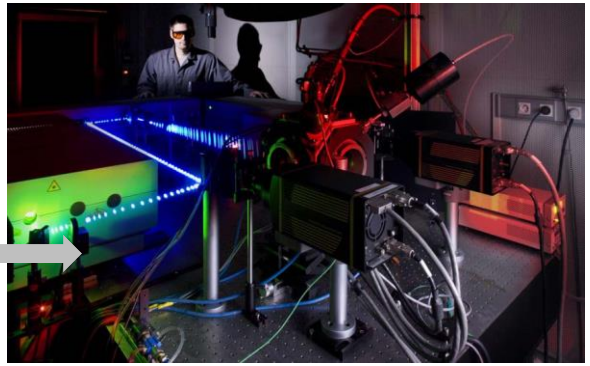
Reconstruction of conduit geometry (PI Mohar)



Acquisition of geometry data by laser imaging (PI Renard)



3D printing of conduits (PI Renard)

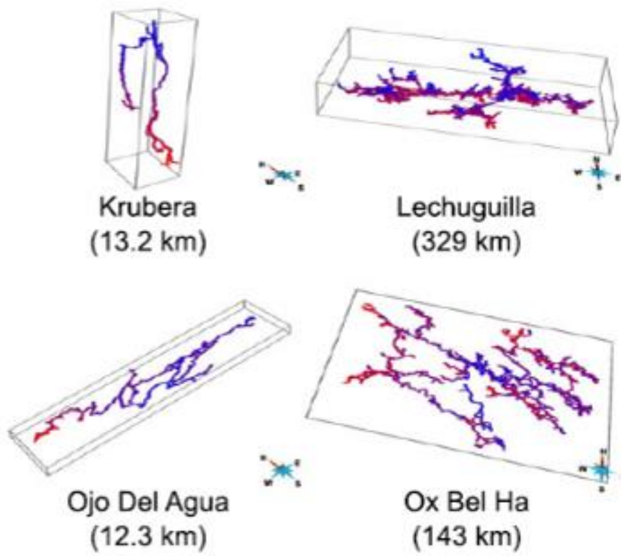


Flow and transport experiments (PI Noetinger)

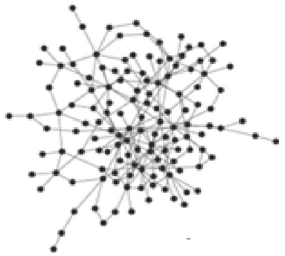
Scientific breakthroughs:
Upscaled equations for water flow and contaminant transport

WP2: Karst network structure

New Open Access Data base

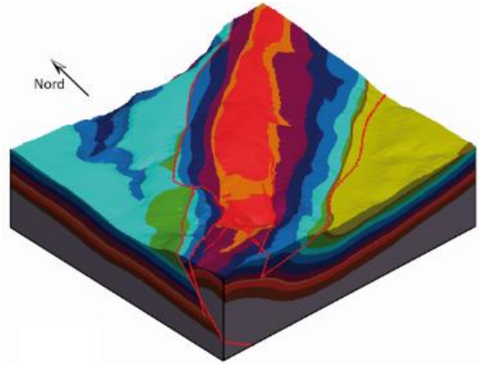


Real networks



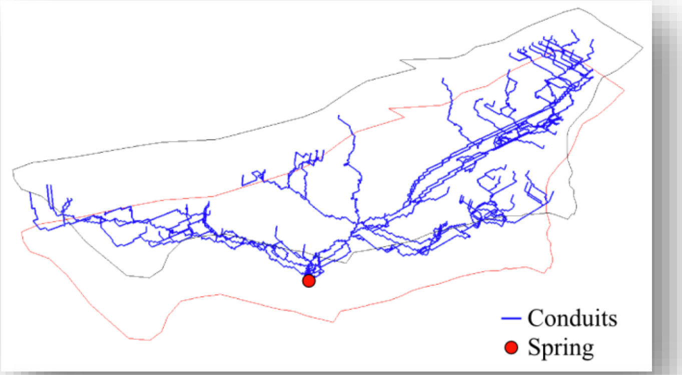
(PI Mohar)

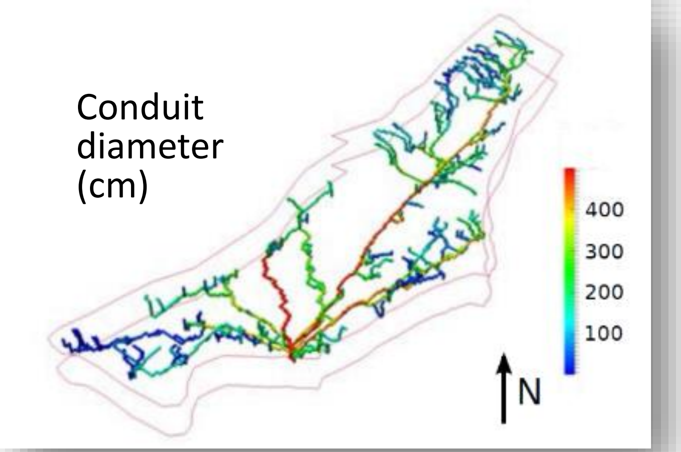
Integrate graph theory with geology



(PI Renard)

Simulated networks

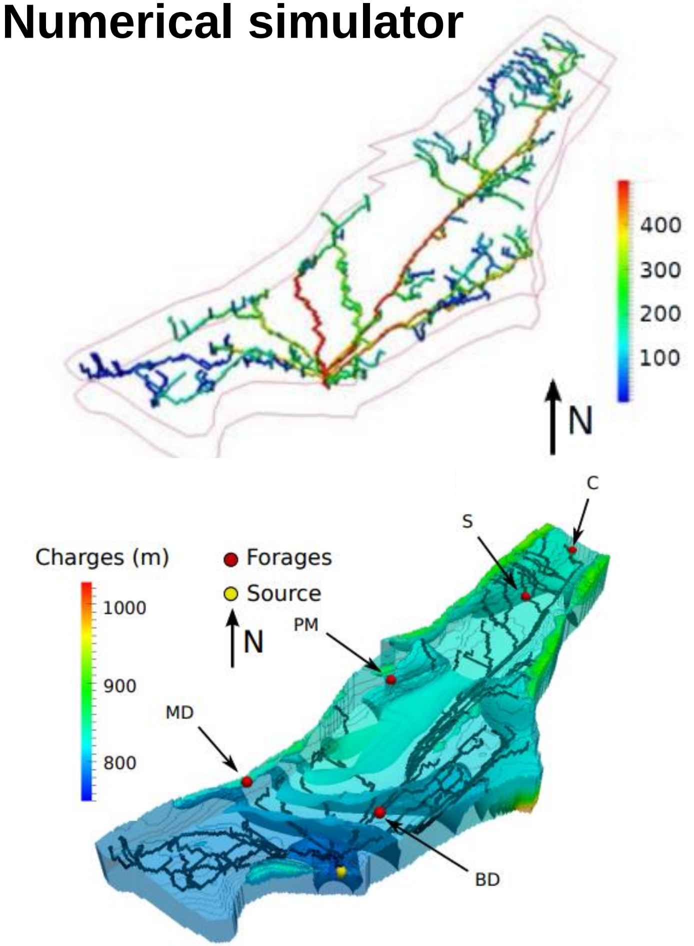




Scientific breakthroughs: Random graphs based on field data and network science

WP3: Physical laws at the network scale

Numerical simulator



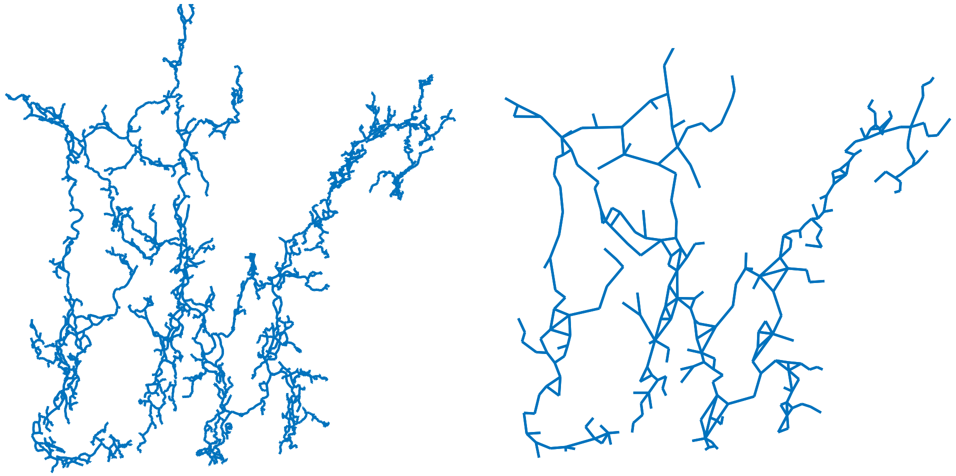
(**All PIs**)

Numerical experiments

Validation

Upscaling

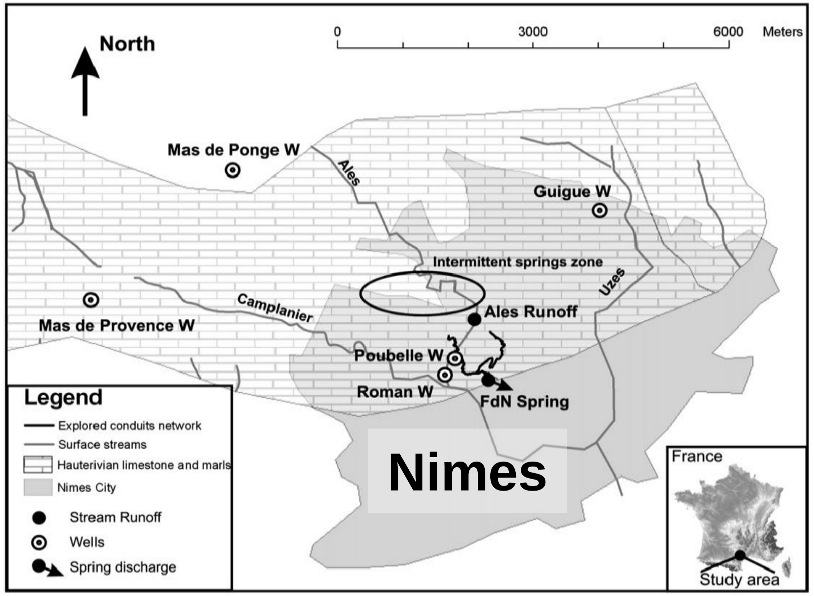
Graph simplification and flow upscaling

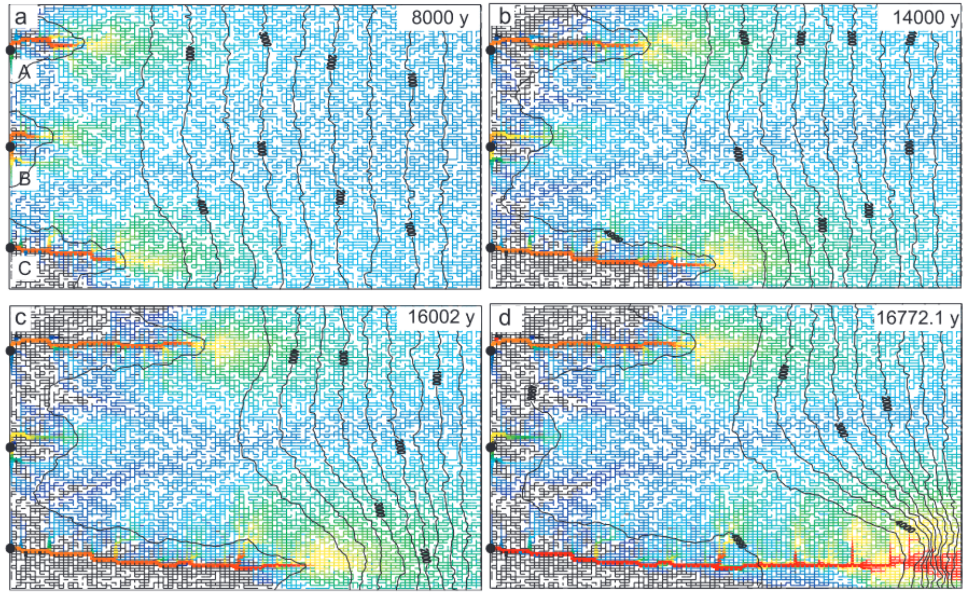


Lagrangian stochastic dynamics

Scientific breakthroughs:
Simulator and upscaled models for mean and extreme behaviors

WP4: Modeling and forecasting





flood **contamination** **karst formation**

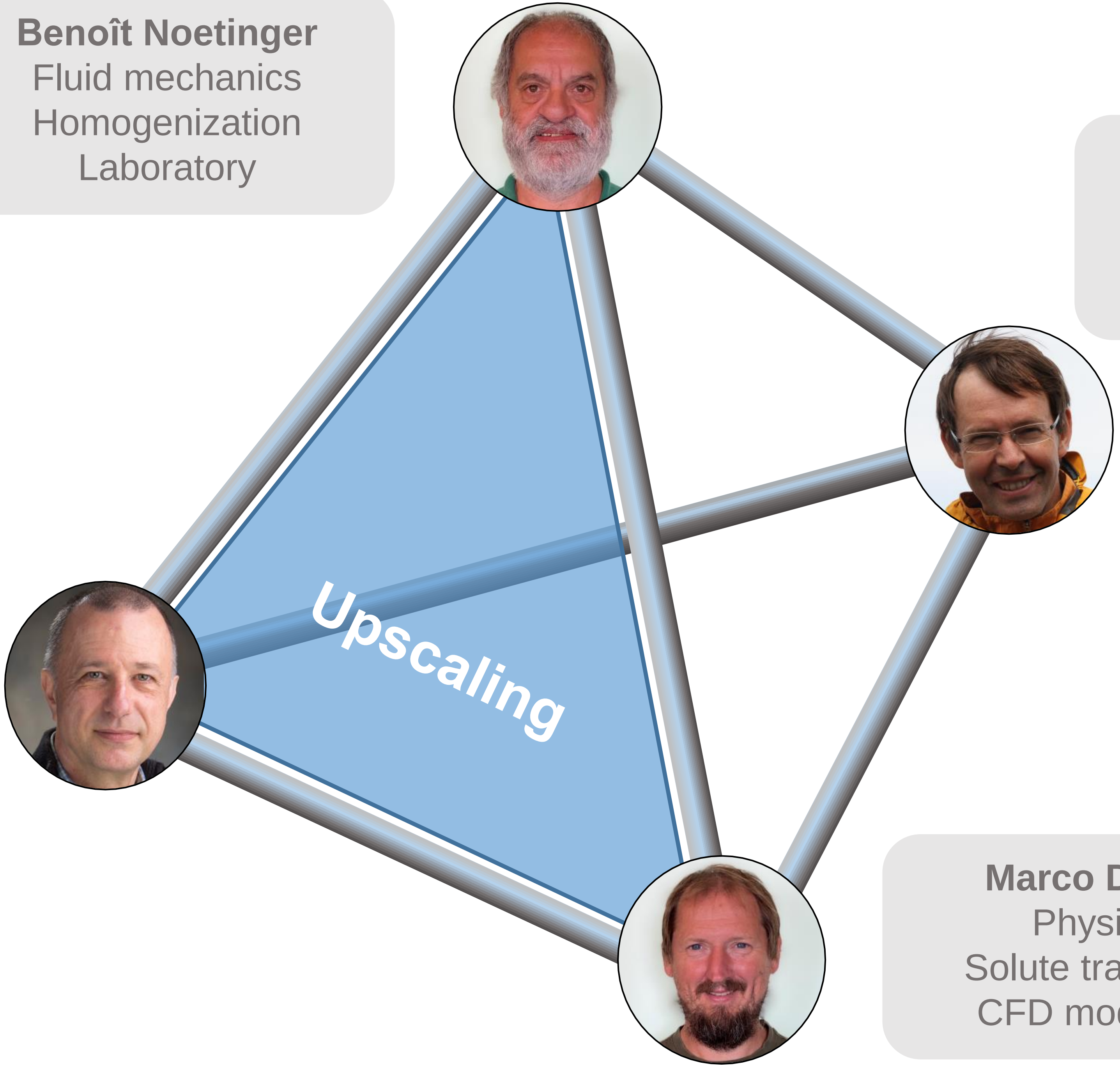
Scientific breakthroughs:
Predictive models of karst behavior under external forcings

Image sources. Left: Fleury et al. (2013), Middle: Demougeot-Renard et al. (2016), Right: Dreybrodt et al (2005)

Synergy

Benoît Noetinger
Fluid mechanics
Homogenization
Laboratory

Philippe Renard
Karst hydrogeology
Spatial statistics
Field work



Bojan Mohar
Mathematics
Graph theory
Network modeling

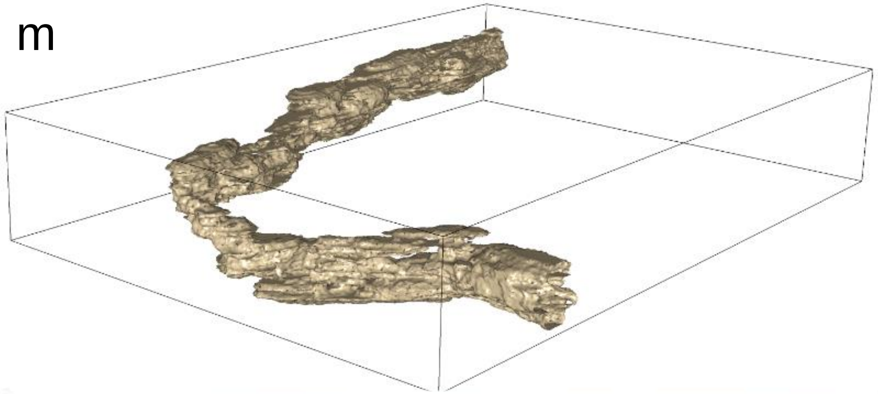
Marco Dentz
Physics
Solute transport
CFD modeling

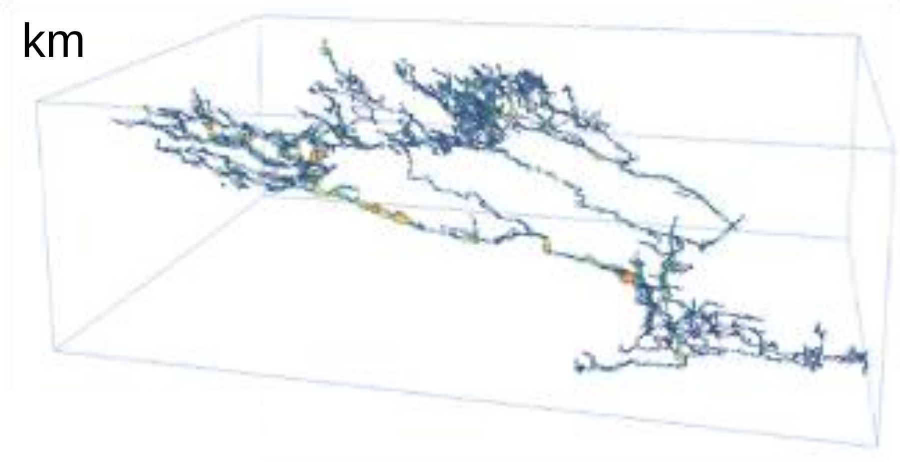
Multi-scale karst theory

From validation of basic physics laws at conduit scale
to comprehensive karst model across the scales.

Synergetic approach never seen before to understand the physics of karst.

Why now? (laser technology, 3D printing, numerical tools, upscaling theory)





Impact of KARST

Physics-based multiscale modeling framework for karst systems

Groundbreaking approach to karst science that was never seen before.

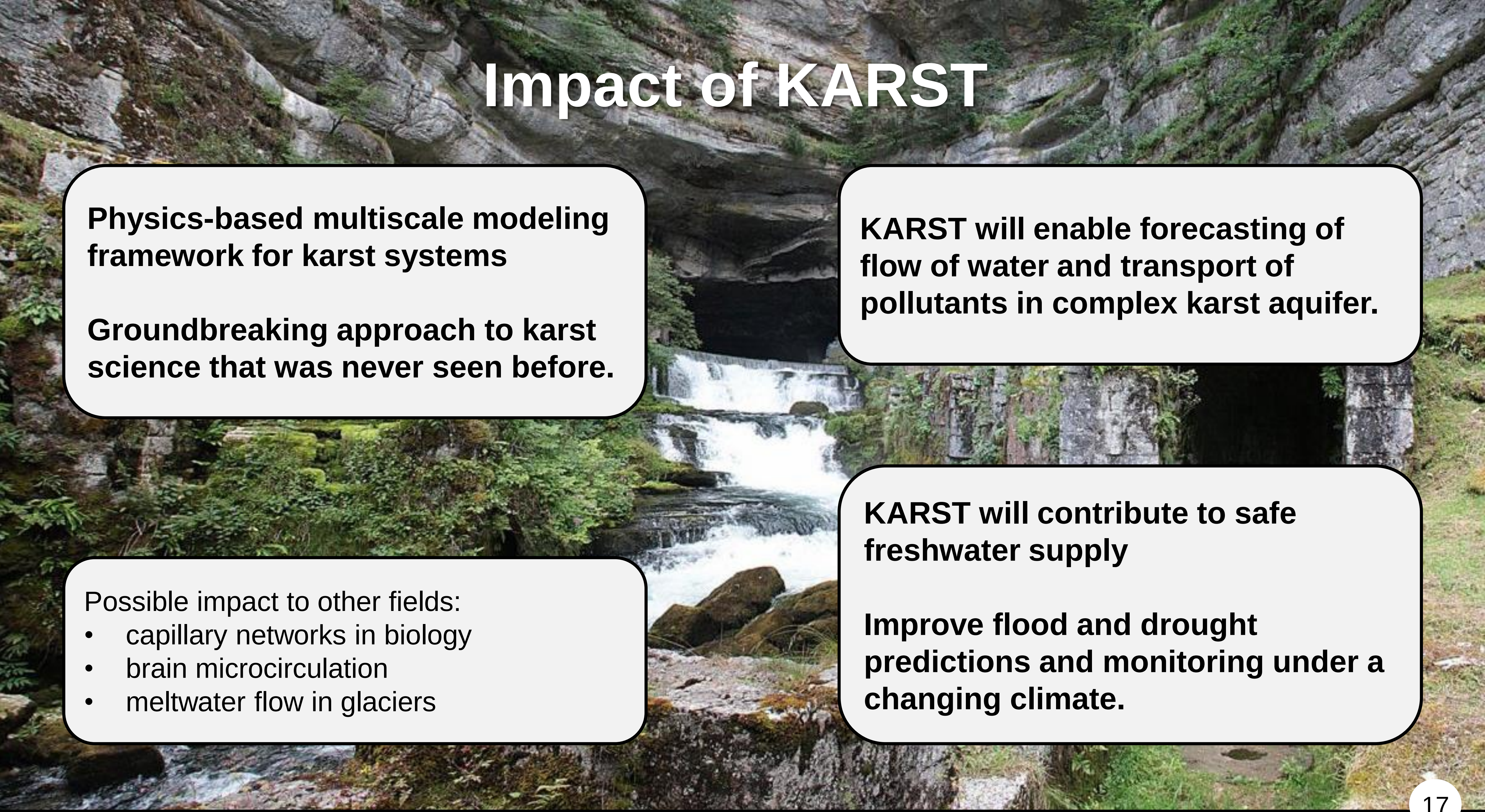
KARST will enable forecasting of flow of water and transport of pollutants in complex karst aquifer.

Possible impact to other fields:

- capillary networks in biology
- brain microcirculation
- meltwater flow in glaciers

KARST will contribute to safe freshwater supply

Improve flood and drought predictions and monitoring under a changing climate.



Loue spring in the Jura, https://www.destinationlouelison.com/decouvrir/les-vallees-de-la-loue-et-du-lison/la-source-de-la-loue/

Karst science breakthroughs	Contributions
Upscaled equations for water flow and contaminant transport on conduit scale	Unprecedented data set on conduit geometry, flow and transport properties
Random graphs based on field data and network science	Unprecedented data base of karst networks
Upscaled models for mean and extreme behaviors	Large-scale coupled numerical simulator
Predictive models of karst dynamic behavior under external forcings	Forecasting of flood and water contamination
Understanding of speleogenesis	Numerical model of speleogenesis

Scientific disciplines	Contributions of KARST project
Geoscience	Karst flow and solute transport modeling, Karst genesis, Understanding the emergence of karst structures
Mathematics	Correlated random graphs & network theory. Homogenization of Laplacian operators on random graphs with random weigths
Physics	Fluid mechanics on tortuous and rough conduits. Anomalous transport on random graphs. Morphogenesis and self-organization in reactive flows. Reactive unsteady CTRW & TDRW
Algorithms / computer science	Diagonalization of very large Laplacian matrices. Graph sparsification

Risks	Mitigation	Gain
WP1: 3D printing of conduits. Unforeseen experimental problems.	Preliminary results on 3D printing. Complementarity of experiment and simulation. Previous experience.	First real data set on conduit flow and transport under controlled condition
WP2: No stochastic classification of network structure possible	Stochastic representation of small-scale network features	Classification and simulation framework for karst
WP3: Dependence on inputs of WP1 and WP2/Upscaling	Modular structure of simulator Integrate complexity progressively	Integration of conduit physics and network structure in large scale predictions
WP4: Dependence of tasks on WP3	Modular structure of simulator. Senior researchers in charge of simulator	Predictive model under external forcing
Different backgrounds and scientific communities of PIs	Innovative strategy for synergy creation, knowledge transfer and capacity building	Unprecedented synergetic approach to advance karst science

Dynamics of synergy and organization

Actions	Implementation
Governance	- Distributed responsibilities, bi-weekly meetings, continuous communication via electronic means, recruiting strategy
Common recruitment strategy	- Common job advertising, and job criteria (e.g., gender equality plan) - Selection committee for PhD and PostDocs - Syncronization of starting dates
Knowledge transfer and training strategy, capacity and skill building (KARST team)	- (month 1) Kick-off meeting - (month 13) Workshop (intro to karst, fluid mechanics, graphs, transport) - (> month 13) Annual workshops (courses/results/coordination) - Bi-annual coordination meetings
Research stays and secondments (throughout the whole project)	- Postdocs and PhD students are co-supervised - Short term (1-4 weeks) and long-term research stays (> 3 months) in the different institutions by all members
Workshops (open to and engaging the different scientific communities)	- Mid-term workshop (3 years, Lorentz center workshop) - End-of-project workshop (6 years, Monte Verita conference)
Integrated research methodology	- Interrelated work package structure and tasks require complementary expertise and synergy between the PIs

Karst team (32 people)

Univ. of Ljubjana

Bojan Mohar

1 Senior Researcher
1 Junior Researcher
4 Postdocs
1 PhD student

IFPEN Paris

Benoît Noetinger

3 Senior Researchers
2 Postdocs
2 PhD students
1 Lab Engineer

Univ. of Neuchâtel

Philippe Renard

1 Senior Researcher
2 Postdocs
2 PhD students
2 Field technicians

CSIC Barcelona

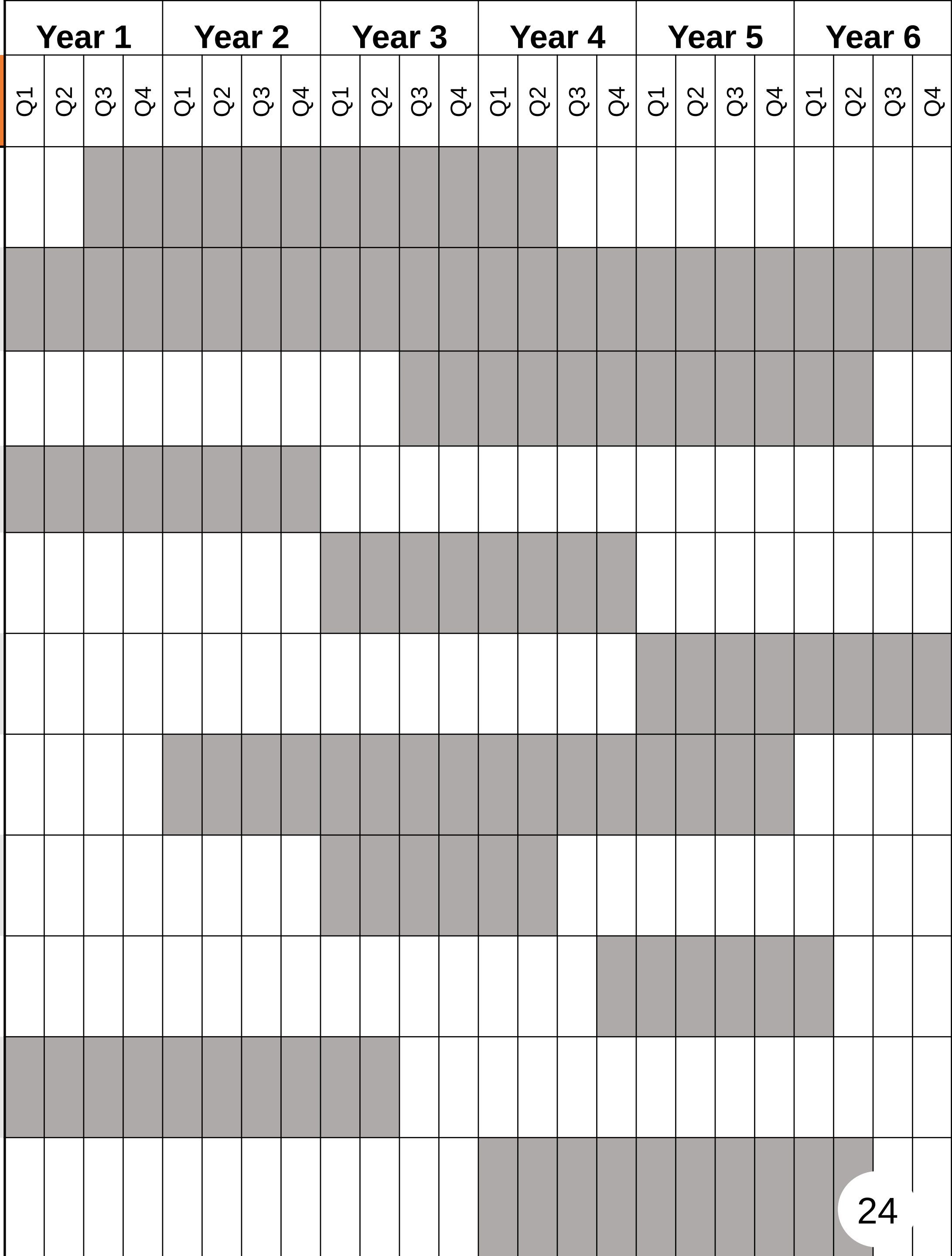
Marco Dentz

1 Senior Researcher
3 Postdocs
2 PhD students

Joint supervision of PhD students

Person	Main supervisor	Second Supervisor	PhD topic	Quarter
PhD 1	Dentz	Renard	Physical laws at conduit scale	Q5-20
PhD 2	Dentz	Noetinger	Transport laws at catchment scale	Q9-24
PhD 3	Mohar	Renard	Graph characterization and simulation	Q5-20
PhD 4	Noetinger	Mohar	Flow equations at catchment scale	Q5-16
PhD 5	Noetinger	Mohar	Evaluating flow response to climate change	Q11-22
PhD 6	Renard	Dentz	Environmental forensic	Q5-20
PhD 7	Renard	Dentz	Physics based modeling of karst formation	Q9-24

PD	Main Tasks	Main affiliation		Strong interactions
1	CFD modeling and upscaling at conduit scale	CSIC	Dentz	Noetinger, Renard
2	Development of numerical tool / catchment scale	CSIC	Dentz	Mohar, Renard
3	Upscaling of transport / catchment scale	CSIC	Dentz	Noetinger
4	Graph characterization	UL	Mohar	Renard, Noetinger
5	Graph simulation	UL	Mohar	Renard
6	Hydrological forecasts and graphs	UL	Mohar	Noetinger
7	Numerical methods for solving PDEs (CFD + catchment)	SFU	Mohar	Dentz
8	Upscaling of flow / catchment scale	IFPEN	Noetinger	Mohar
9	Flow response / Nimes	IFPEN	Noetinger	Mohar, Renard
10	Cave geometry data acquisition and modeling	UNINE	Renard	Mohar, Noetinger
11	Karst formation	UNINE	Renard	Dentz, Mohar

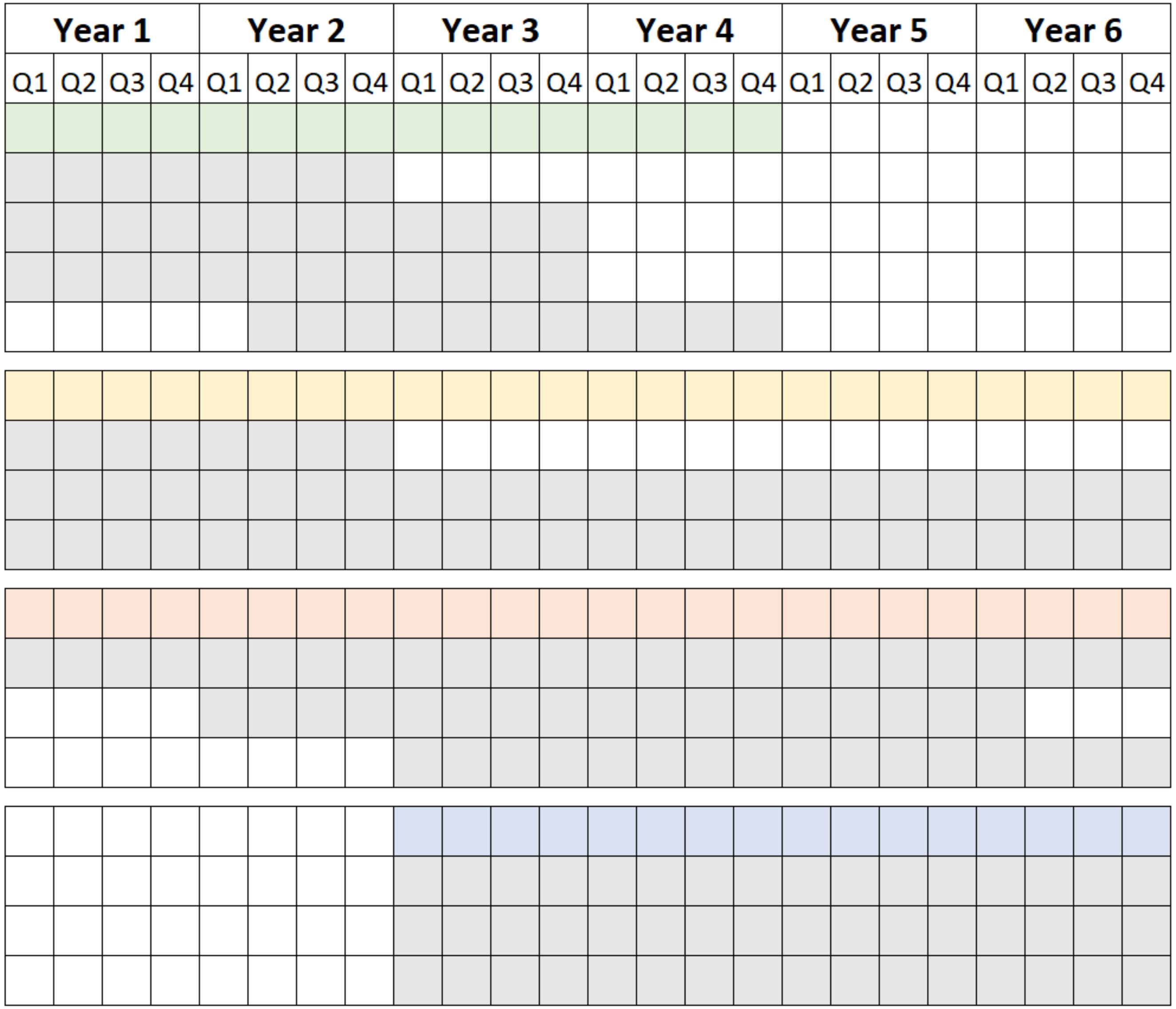


Main hypotheses

- Hypothesis 1: **Classical methods do not work** (additional parameters/new equations are needed)
- Hypothesis 2: **It is possible to arrive at stochastic network representations that are representative of real karst networks**
- Hypothesis 3: **Flow and transport laws at catchment scale can be derived** (in contrast to data-driven approach hypotheses)

Structure of KARST

		PI Teams			
WP1	**Physical laws at individual conduit scale**	1	2	3	4
T1.1	Individual cave geometry		x	x	L
T1.2	Flow and transport experiments	x		L	x
T1.3	CFD flow and transport experiments	L	x	x	x
T1.4	Flow and transport laws at conduit scale	L		x	x
WP2	**Karst network structure**	1	2	3	4
T2.1	Data collection network geometry		x	x	L
T2.2	Graph characterization and analysis		L	x	x
T2.3	Simulating cave networks	x	L	x	x
WP3	**Physical laws at the network scale**	1	2	3	4
T3.1	Develop a numerical simulator	L	x	x	x
T3.2	Upscaling of flow	x	x	L	x
T3.3	Upscaling of transport	L		x	x
WP4	**Modeling and forecasting**	1	2	3	4
T3.1	Droughts, flash floods and climate change		x	L	
T3.2	Environmental forensic	x		x	L
T3.3	Emergence of specific karst structures	x	x	x	L



1 = Dentz, 2 = Mohar, 3 = Noetinger, 4 = Renard