

# **Microbial communities through the lens of high throughput sequencing, data integration and metabolic networks analysis**

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**developing computational approaches to better understand microbial assemblages**

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PhD candidate



# Microbial ecology & biogeochemical cycles

a corner-stone for life on earth

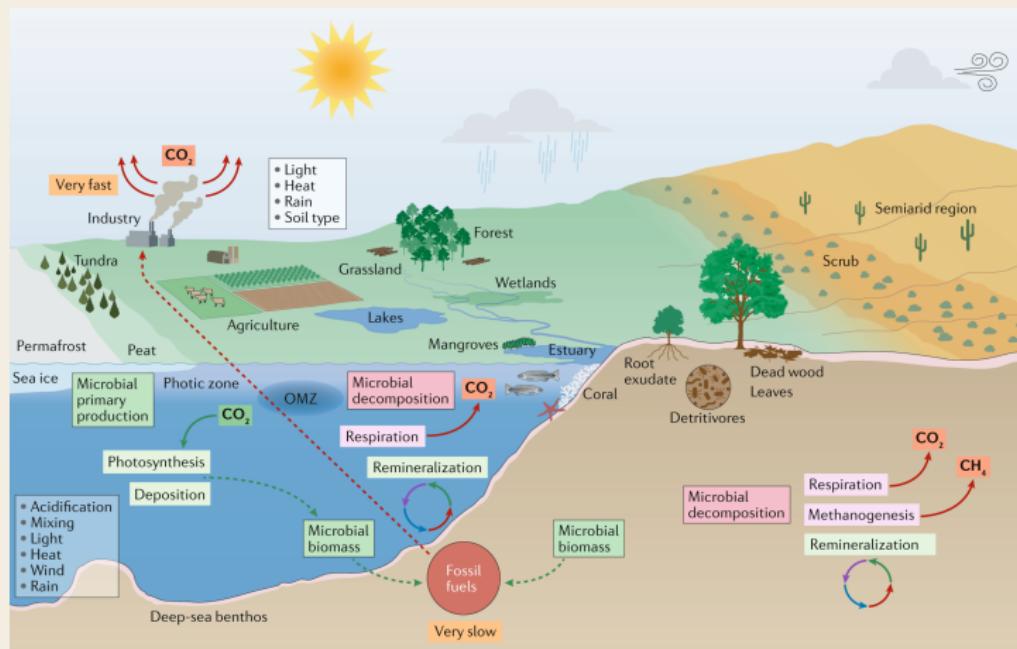


Figure from: Nature Reviews Microbiology 17.9 (2019): 569-586.

# Main questions regarding a microbial community for a deeper understanding of such assemblages



community  
structure  
**who**

*taxa, abundance*



ecosystem  
type  
**where**

*habitats*



functional  
potential  
**what**

*processes*

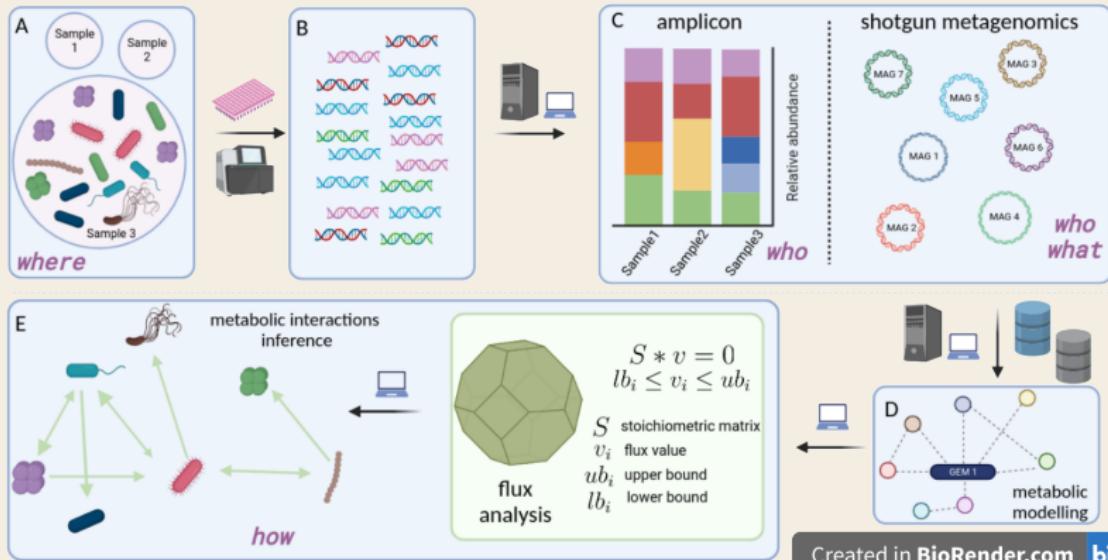


underlying  
mechanisms  
**how**

*interactions, fluxes*

# Reverse ecology

transforming ecology into a high-throughput field



Created in BioRender.com

# From raw reads to community analysis

*not a straight-forward way*

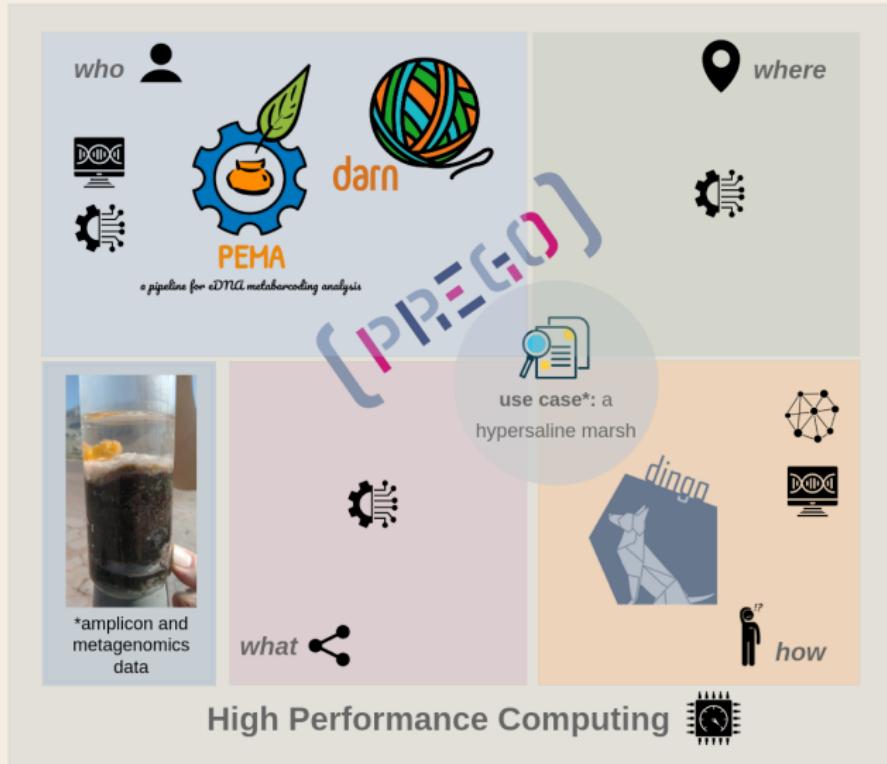
- sequencing technology oriented
- eDNA-, sample process-, primers-, PCR-oriented
- complex bioinformatics analysis
- analysis reproducibility
- computing requirements
- algorithm-oriented
- versioning of reference databases & tools
- standards, ontologies
- data integration applications



## Aims and objectives

- build algorithms and software to address on-going challenges in microbiome data analysis
- identify taxa & functions with a key role in microbial community assemblages in hypersaline sediments

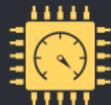
# Graphical abstract of this PhD thesis



Legend	
	data integration
	HTS
	metabolic modelling
	HPC

# Os and 1s in marine molecular research

*a regional HPC*



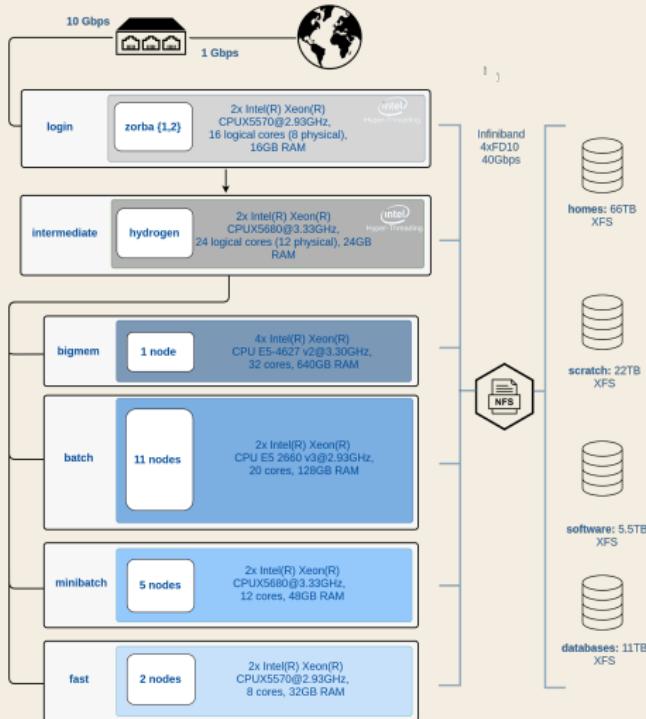
**challenge category:** computing requirements

**aim & contribution:** to present insights from a thorough analysis of the research supported by the IMBBC HPC facility



# Zorbas: the HPC facility of IMBBC

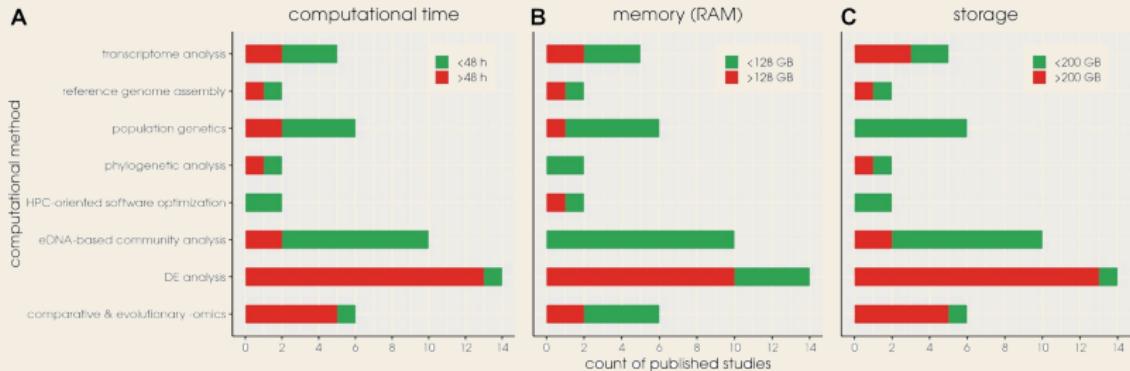
## a Tier 2 (regional) HPC facility



Block diagram of the  
Zorba architecture



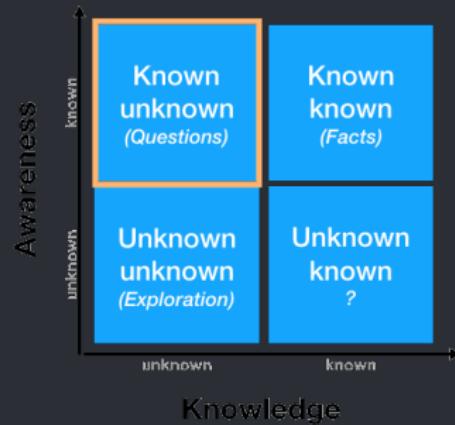
# Computational requirements for trivial bioinformatic tasks



Red bars denote published research with high resource requirements  
of the various computational methods employed at the IMBBC HPC facility



# Bioinformatics challenges for the analysis and the interpretation of amplicon data



- multiple steps
- several tools & databases
- computing power
- scalability & reproducibility

OTUs/ASVs with no taxonomy assignment:  
novel or non-target taxa

# PEMA

*a flexible Pipeline for Environmental DNA Metabarcoding Analysis*



**challenge category:** complex bioinformatics analysis, analysis reproducibility

## aim & contribution

To build an open source pipeline that bundles state-of-the-art bioinformatics tools for amplicon analysis that is:

- a one-stop-shop for several marker genes & approaches
- easy-to-set & easy-to-use
- scalable & flexible
- reproducible

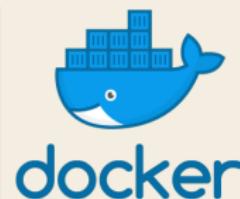


# Methods / Implementation

*PEMA coding insights*

```
for(int i : range(1,  
    in := "in_$i.tx  
    sys date > $in  
  
    out := "out_$i.t  
    task( out <- in  
        sys echo Tas  
    }  
,
```

Big-  
DataScript  
programming  
language



Containerization

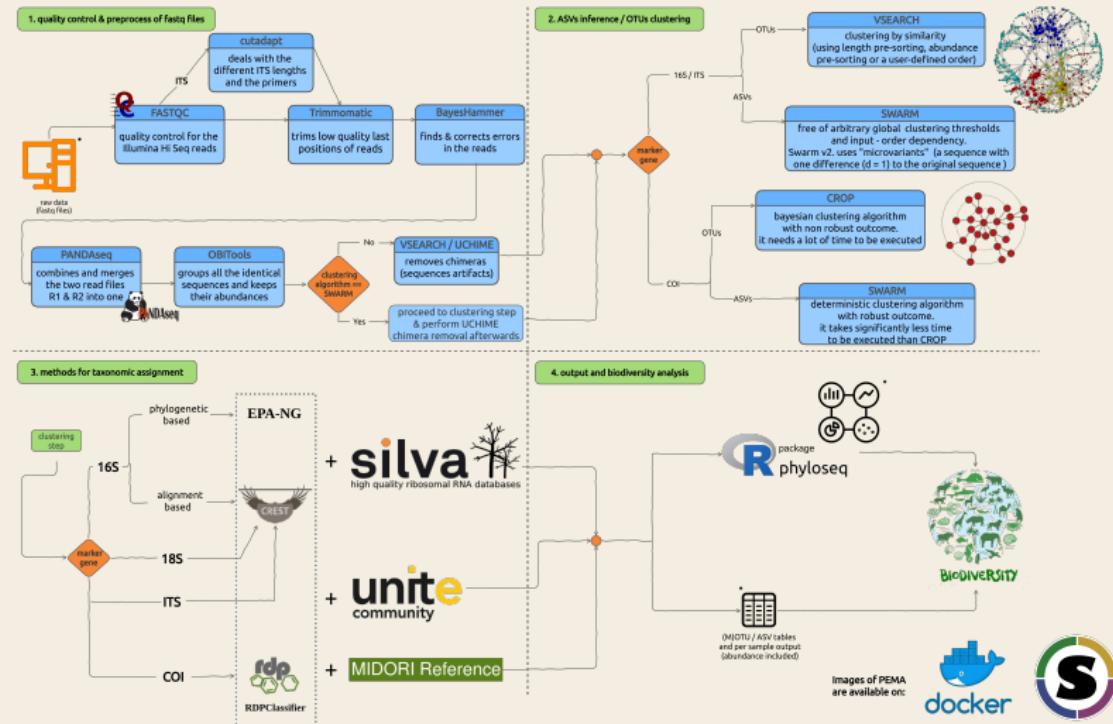
High performance  
computing



# PEMA features

## an overview

### PEMA in a nutshell





# Results: tuning effects in mock communities

Mock communities using the 16S rRNA gene and multiple parameter sets  
(identification at the genus level; part of the initial table):

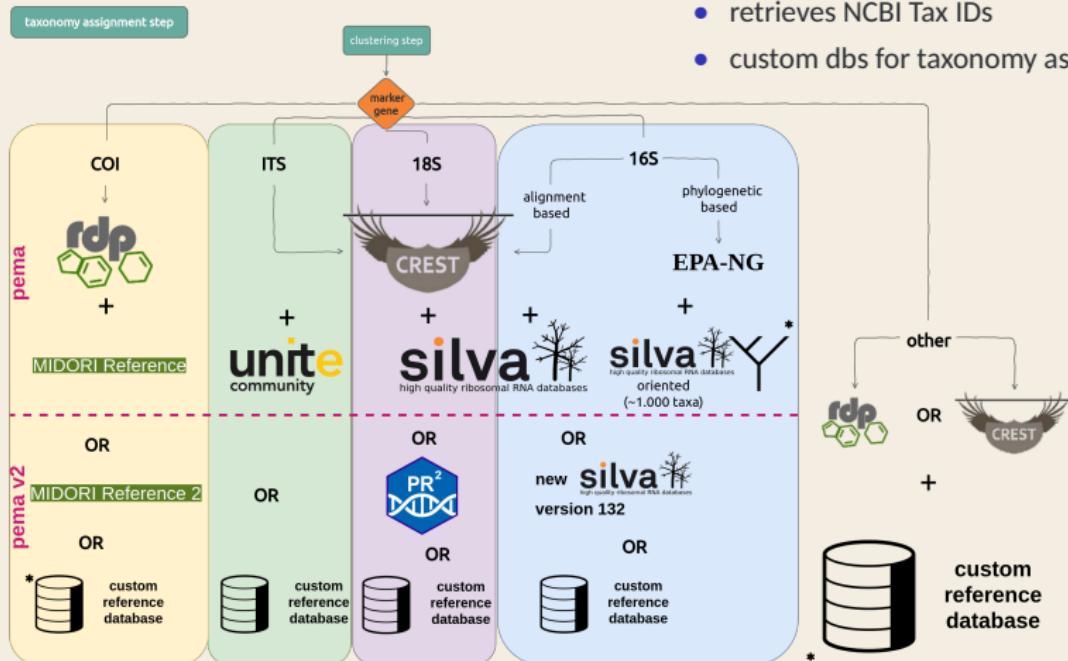
mock community Gohl et al. (2016)	Swarm (d = 1 strict = 0.8 no singletons)	Swarm ( d = 3 strictness = 0.6 no singletons)	Swarm ( d = 3 strictness = 0.8 with singletons)	Swarm ( d = 10 strictness = 0.8 with singletons)	Swarm ( d = 10 strictness = 0.8 no singletons)	Swarm ( d = 25 strictness = 0.6 )	Swarm ( d = 25 strictntess = 0.8 )	Swarm ( d = 30 strictness = 0.6 )
TP	12	15	18	18	15	17	17	17
FP	2	2	21	11	6	5	5	4
FN	8	5	2	2	5	3	3	3
PREC (TP / TP+FP)	0.86	0.88	0.46	0.62	0.71	0.77	0.77	0.81
REC (TP / TP+FN)	0.6	0.75	0.9	0.9	0.75	0.85	0.85	0.85
F1 (2 * (PREC * REC) / (PREC+REC))	0.71	0.81	0.61	0.73	0.73	0.81	0.81	0.83



# PEMA v.2

## addressing some of the challenges

- new code architecture
- 12S rRNA now supported
- retrieves NCBI Tax IDs
- custom dbs for taxonomy assignment



\* Illustrations with an asterisk are from the Noun Project.



# Moving at the large scale

## PEMA @ infrustuctures

The screenshot shows the Tesseract VRE Development Portal interface. On the left is a sidebar with categories like 'Personal space', 'ARMS', 'Biotope', 'Cytoscape functional topographies', 'Metagenomics', and 'Tools'. The main area is titled 'Run a ARMS workflow' and shows a 'Workflow overview' with a diagram of four steps: 'Import TSV' (with 'Param file' and 'Import file' sub-steps), 'PEMA' (with 'csv / tsv' and 'Ondiskable' sub-steps), 'WaRMS' (with 'Ondiskable' sub-step), and 'WRMS' (with 'Tab dataset' sub-step). Below the diagram are steps: 'Workflow description', 'CSV input data', 'PEMA parameters', 'Create workflow', and 'Workflow created'. At the bottom left is a 'Save theme' button.

LifeWatch ERIC:  
[www.lifewatch.eu/](http://www.lifewatch.eu/)

Tesseract VRE Development Portal:  
[www.lifewatch.dev/dashboard](http://www.lifewatch.dev/dashboard)

1. Web - interface make analysis even easier
2. researchers without access to HPC/clouds etc are now able to run big scale analyses
3. Combine with other tools

Elixir Greece:  
<https://elixir-greece.org/>  
Hypatia cloud infrastructure:  
<https://hypatia.athenarc.gr/>



# Conclusions

## on PEMA and eDNA metabarcoding

- **parameters tuning** is essential in metabarcoding analyses; **mock communities** among samples under study benefit to that end
- workflow managers & containers enable complex and reproducible workflows
- **e-infrastuctures** benefit studies with great number of samples and CLI non-familiar users

# DARN

*dark matter investigator tool*



**challenge category:** eDNA - oriented issues

**aim & contribution:**

extract "dark matter" from COI amplicon data

i.e. non-target, unassigned or assigned with low confidence sequences.



# Building a COI-oriented tree of life

## sequences retrieved

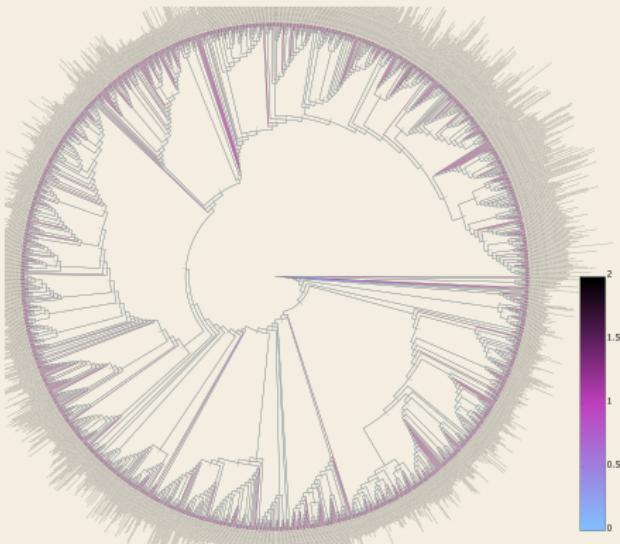
Resources	bacteria		archaea		eukaryotes	
	# of sequences	# of strains	# of sequences	# of strains	# of sequences	# of species
BOLD	3,917	2,267	117	117		
PFam-oriented	9,154	4,532	217	115		
Midori 2					1,315,378	183,330
Total unique entries	11,421	6,798	334	201	1,315,378	183,330



	bacteria	archaea	eukaryotes
consensus sequences (tree branches)	463	25	1,109



## Reference phylogenetic tree of the COI consensus sequences retrieved

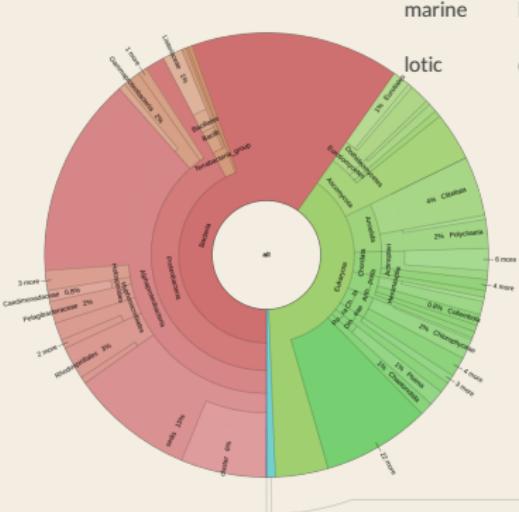


the consensus sequences have been placed in their corresponding taxonomic branches, proving the tree valid



## DARN using real-world data

with multiple sample types, primers, PCR protocols and bioinformatics pipelines



Env type	Sample type	Bioinfo pipeline(s)	# of ASVs	~% of sequence assignments per domain		
				eukaryotes	bacteria	archaea
marine	eDNA	QIIME2 - Dada2	13,376	11	88	0.02
		PEMA (d=10)	39,454	25	75	0.1
marine	bulk	PEMA (d=2)	193	99	1	-
		PEMA (d=2)	74	97	0	-
lotic	eDNA	PEMA (d=10)	1,940	64	34	2

More results at: <https://hariszaf.github.io/darn/>



# Conclusions

on DARN and COI amplicon studies

- dark matter is widely common in eDNA samples compared to bulk ones
- bacteria make up a significant proportion of sequences generated in COI based eDNA metabarcoding datasets
- including non-eukaryotic COI sequences in reference databases could benefit the method

# dingo

*a new MCMC algorithm for sampling the flux Space of metabolic networks*



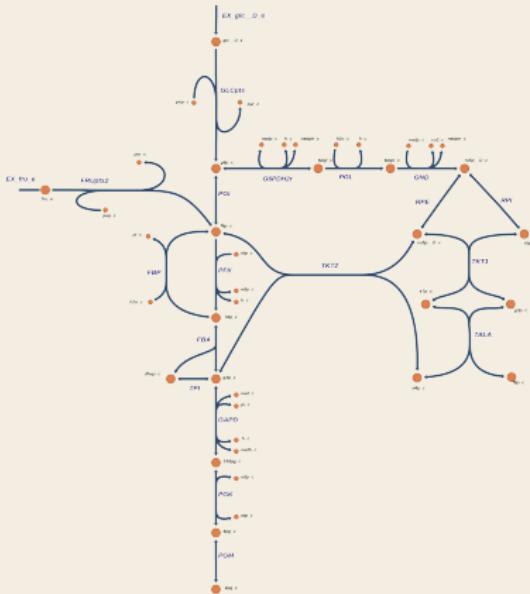
**challenge category:** algorithm-oriented

**aim & contribution:**

support flux sampling at high dimensional polytopes such as those of complex organisms and multispecies and/or host-microbe communities



# Metabolic modelling and the biomass function



Metabolic models allow us to move from a metabolic map to mathematical structures the study of which may provide fundamental biological insight

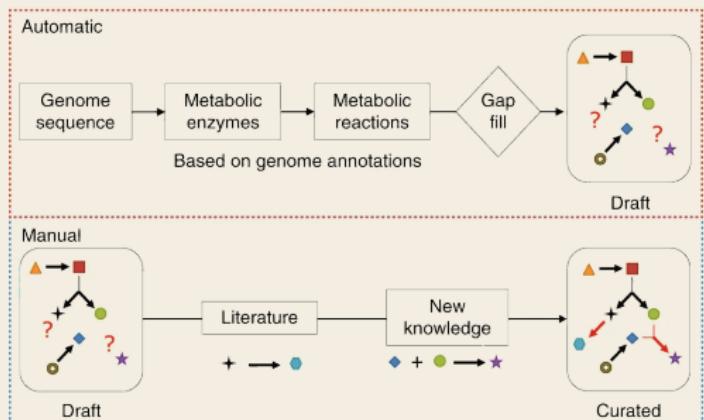


Figure from: Heirendt et al. Nature protocols 14.3 (2019): 639-702.



# From a stoichiometric matrix to a constraint-based model

Reactions

	R <sub>1</sub>	R <sub>2</sub>	R <sub>3</sub>	R <sub>4</sub>	R <sub>5</sub>
Metabolites	-1	0	0	0	0
▲	1	-1	0	0	0
■	0	1	-1	0	0
●	0	1	0	0	-1
◆	0	0	1	0	0
○	0	0	0	-1	0
◆	0	0	0	1	-1
★	0	0	0	0	1

S-matrix

$\times$

Flux vector

$$\begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \\ v_5 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

In a **steady state**  
the production rate  
of each metabolite  
equals its consumption rate

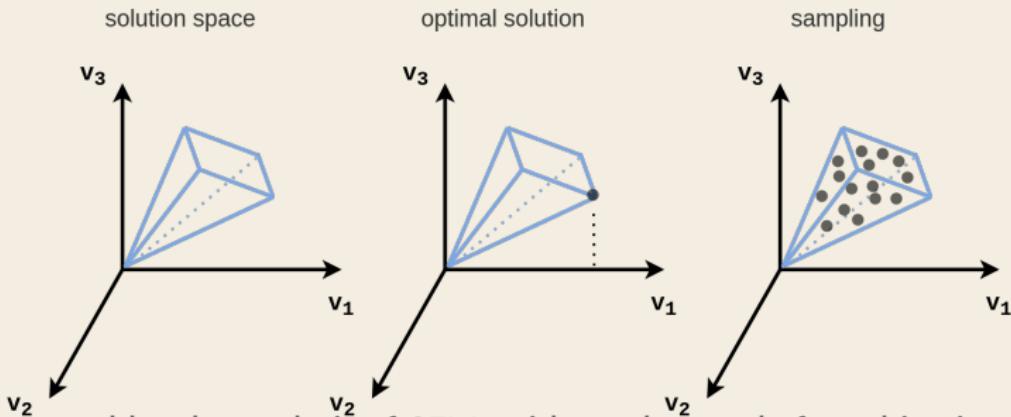
The **flux vector** is a vector with  
the value of  
each reaction flux  
in a certain steady  
state.

The steady state assumption  
is ensured by  
the **zero-vector**.



# Flux sampling

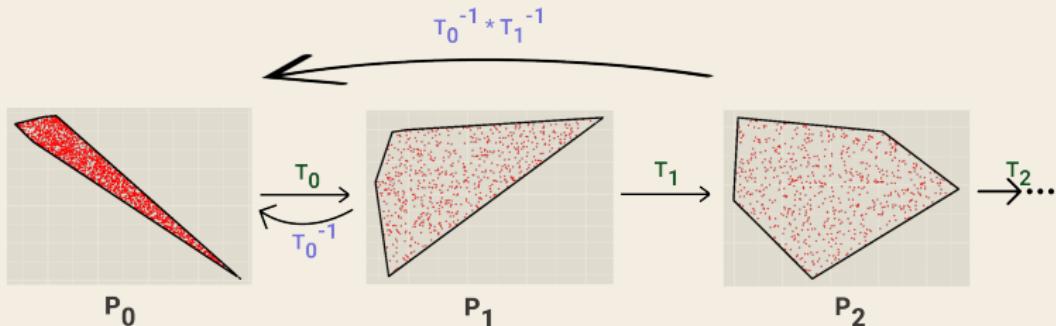
*an alternative approach*



- enables the analysis of GEMs without the need of an objective function
- determines the feasible solution spaces for fluxes in a network based on a set of conditions as well as the probability of obtaining a solution



# A new Markov Chain Monte Carlo algorithm for flux sampling



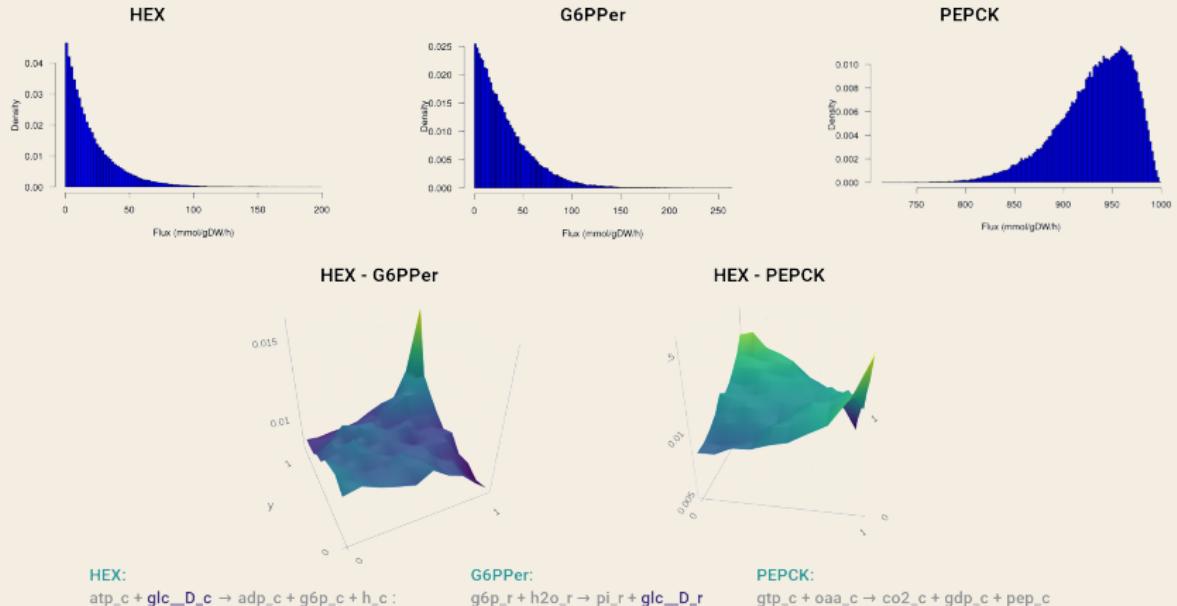
## Steps of an MMCS phase

- **sampling step:** using a variant of the **Billiard walk**
- **rounding step:** calculate a linear transformation  $T_i$  that puts the sample into isotropic position and then apply it on  $P_i$  to obtain the polytope of the next phase
- check several statistic tests



# Flux sampling output

## *marginal distributions and copulas*





# Conclusions

*on sampling the flux space of metabolic models*

- flux sampling provides essential insight (knock-out genes, host-microbe interactions etc)
- our multiphase MCMC algorithm enables sampling on the so-far largest metabolic model (Recon3D including 13, 543 reactions;  $d = 5, 335$ ) is now possible
- sampling the flux space of community metabolic models is now possible

# PREGO

*a literature- and data-mining resource to associate  
microorganisms, biological processes & environment types*



**challenge category:** data integration applications

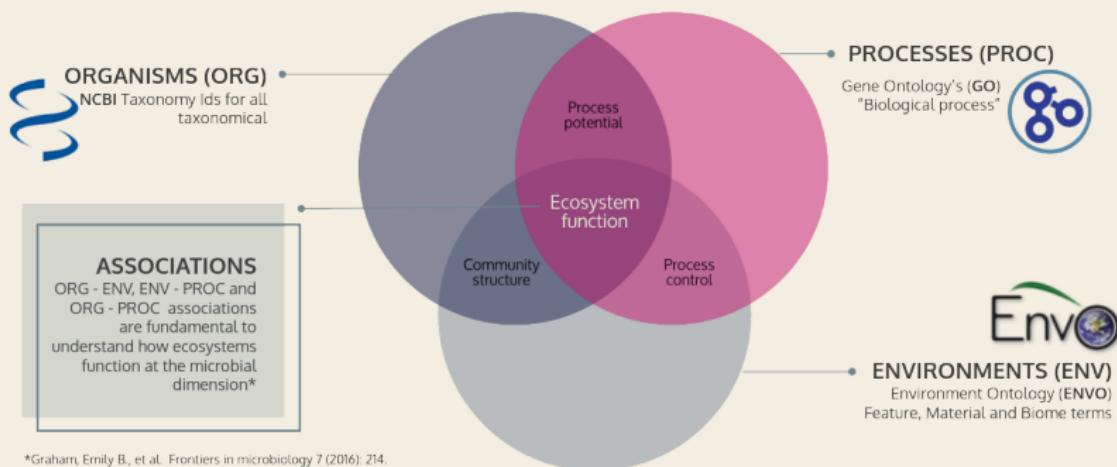
## **aim & contribution:**

To build a hypothesis generation resource based on associations between:

- *organisms and the environments they inhabit*
- *organisms and the biological processes they are involved with*
- *processes and the environments where they occur*

# PREGO and its referring terms

## *the fundamental role of ontologies*



\*Graham, Emily B., et al. Frontiers in microbiology 7 (2016): 214.

# Named Entity Recognition

counting co-occurrences to export associations

Identification of potentially important pathways missing from the model

EXTRACT	X
Protein	
Chemical compound	
Organism	
Environment	
Tissue	
Disease/phenotype	
Gene Ontology term	

From the metagenomic bins, we were able to identify two **metabolic processes** that were not previously included in the model. A number of MAGs (bin.59, bin.15, bin.73) clustered to the KEGG genomes of **freshwater sulfur**-oxidizing autotrophs capable of denitrification, *Sulfuritalea hydrogenivorans* [41], and *Sulfuricella denitrificans* [42]. These MAGs contained the diagnostic genes for **carbon fixation** (*rbcL.S*), **sulfur** cycling (*dsrAB*), and denitrification (*nosZ*). One MAG (bin.59) also clustered with **iron** oxidizing autotroph *Sideroxydans lithotrophicus ES-1*. Bin.59 is the most relatively abundant bin from 17 to 21 m depth. Thus, if this MAG is associated with **iron** oxidation, it also contains **sulfur**-cycling genes that add to metabolic flexibility, which was previously observed [40]. The model did not include **sulfide oxidation** with **nitrate**, so it is unclear from the current model predictions where this process is expected to occur within the water column to compare to the MAG distributions.

Example text from Arora-Williams et al. Microbiome 6.1 (2018): 1-16.

# Publicly available omics data sets and the role of metadata

Sample metadata [-]



Collection date:	11/1/11
Elevation:	200
Environment (biome):	soil
Environment (feature):	nosZ
Environment (material):	soil DNA
Environmental package:	MIGS/MIMS/MIMARKS.soil
Geographic location (depth):	15-20cm
Instrument model:	454 GS FLX Titanium
Investigation type:	metres-survey
NCBI sample classification:	410658
Project name:	EcoFINDERS

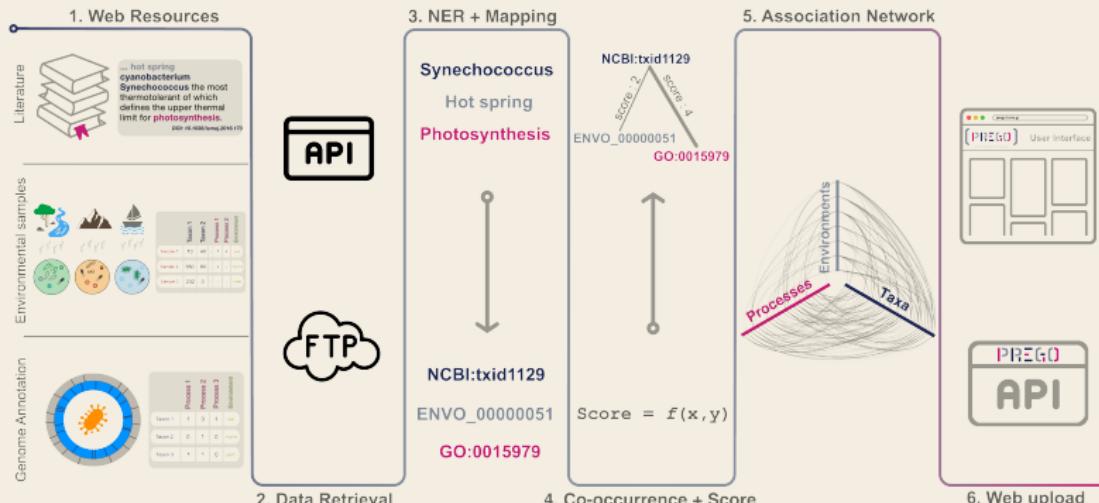
Project Information	
Cultured	No
Ecosystem	Environmental
Ecosystem Category	Aquatic
Ecosystem Subtype	Oceanic
Ecosystem Type	Marine

**MG-RAST**  
metagenomics analysis server

MG-RAST ID	name	biome	feature	material	sample	library	location	country	coordinates	download	
mgm4702467.3	06032015b_S2_L001_R2_001	Large lake biome	lake	water	mgs485560	mg485562	Cincinnati	USA	39.11, -84.5	 	
mgm4702469.3	06052015a_S3_L001_R2_001	Large lake biome	lake	water	mgs485566	mg485568	Cincinnati	USA	39.11, -84.5	 	
mgm4702471.3	06032015a_S1_L001_R2_001	Large lake biome	lake	water	mgs485554	mg485556	Cincinnati	USA	39.11, -84.5	 	

# PREGO methodology

3 channels of information - 1 framework



# Source databases that are integrated in PREGO and the number of items retrieved



Source	# Items	Data Type	Metadata	License
MEDLINE and PubMed	33 million	abstracts (text)	no	NLM Copyright
PubMed Central OA Subset	2.7 million	full article (text)	no	CC for Commercial, non-commercial
JGI IMG	9,644	Isolates Annotated genomes	yes	JGI Data Policy
Struo	21,276	Annotated genomes	no	MIT, CC BY-SA 4.0
BioProject	18,752	Annotated genomes with abstracts (text)	yes	INSDC policy
MG-RAST	16,096	marker gene samples	yes	CCO
	7,965	metagenomic samples	yes	CCO
MGnify	10,500	marker gene samples	yes	CC-BY, CCO

# PREGO in action

*looking for environments a taxon is present*

Desulfatiglans anilini DSM 4660 [1121399]

Synonyms: Desulfatiglans anilini DSM 4660, D. anilini DSM 4660, D anilini DSM 4660, Desulfatiglans DSM 4660, Desulfatiglans str. DSM 4660 ...

Environments   Biological Processes   Molecular Function   Documents   Downloads

## Literature

Search:

Name	Z-score	Confidence
Oil seep	3.0	★★★★★
Marine mud	3.0	★★★★★
Marine sediment	2.8	★★★★★
Brackish water	2.4	★★★★★
Oil reservoir	2.2	★★★★★
Anaerobic sediment	2.0	★★★★★
Cold seep	1.8	★★★★★
Contaminated sediment	1.7	★★★★★
Neritic sub-litoral zone	1.4	★★★★★
Oil spill	1.4	★★★★★
Petroleum	1.1	★★★★★
Sea floor	1.1	★★★★★

Showing 1 to 12 of 12 entries

Environments   Biological Processes   Molecular Function   Documents   Downloads

## Literature

Search:

Name	Z-score	Confidence
benzoyl-CoA catabolic process	4.3	★★★★★
Benzene catabolic process	3.6	★★★★★
Acetone metabolic process	3.5	★★★★★
Phenanthrene catabolic process	3.5	★★★★★
Sulfate reduction	3.3	★★★★★
Ketone body catabolic process	3.2	★★★★★
Naphthalene catabolic process	3.2	★★★★★
Alkane catabolic process	3.1	★★★★★
Benzoate catabolic process	3.0	★★★★★
Denitrification pathway	2.8	★★★★★
Sulfide ion homeostasis	2.6	★★★★★
Ketone catabolic process	2.6	★★★★★
Methanogenesis	1.8	★★★★★
Electron transport chain	1.0	★★★★★

Showing 1 to 14 of 14 entries

The PREGO knowledge-base is available at  
<http://prego.hcmr.gr/>.

# Conclusions

on PREGO and its associations

- metadata can give substantial added value in experimental data
- taxonomy and ontological-related challenges limit data integration methods
- data integration methods may lead to associations not mentioned in the literature
- the *Environmental Samples* channel will provide more and more associations as omics' dataset keep increasing exponentially

# Deciphering the functional potential of a hypersaline marsh microbial mat community

*Aim of the study and contribution*



To exploit state-of-the-art methods to identify taxa and functions that play a key part in microbial community assemblages in hypersaline sediments



# Tristomo swamp in Karpathos

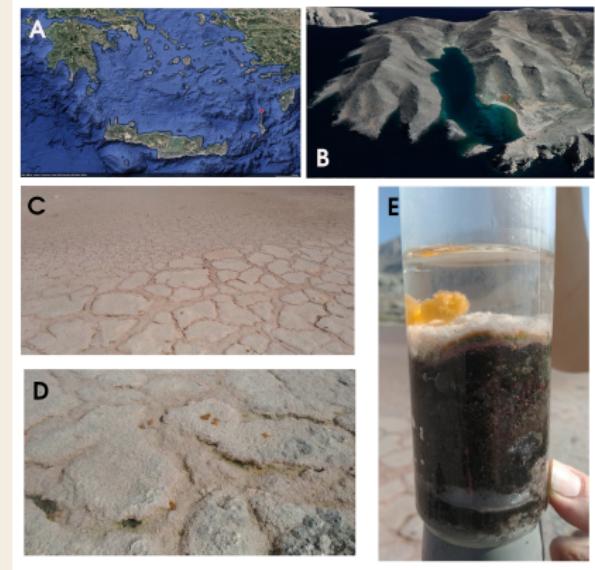
*a seasonal brackish water marsh*

Type of samples:

- from clearly observed mats, top - bottom layers
- if no clearly observed mats samples with no slicing
- aggregate samples

Sampling time points:

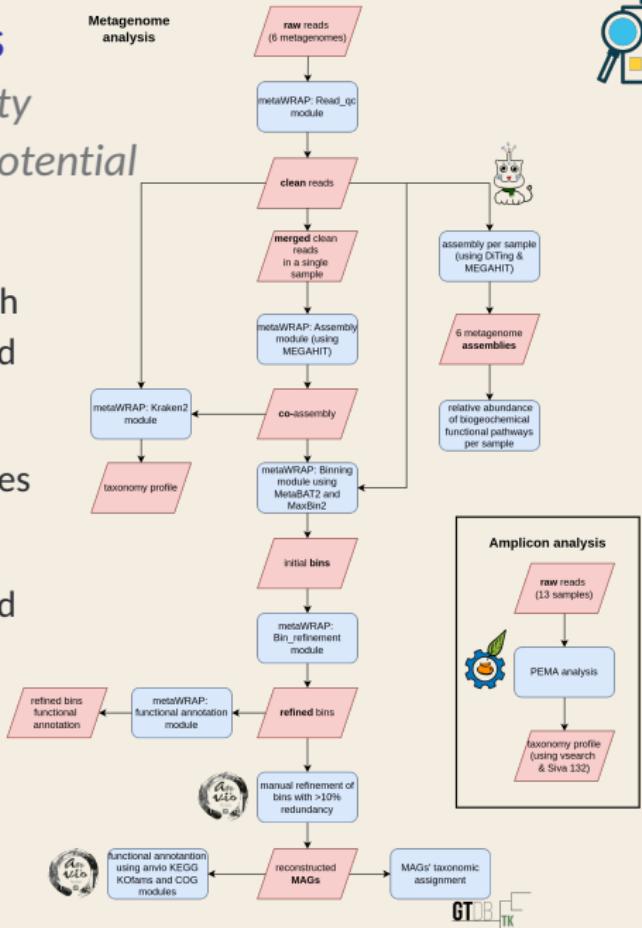
- July 2018
- November 2019



# Bioinformatics analysis from raw data to community composition & functional potential

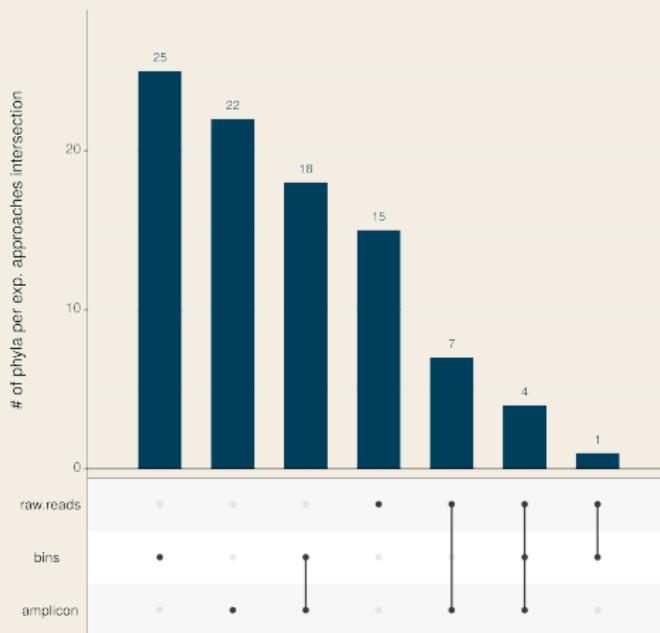


- metagenomic reads were both co - assembled and assembled at the sample level
- taxonomic & functional profiles per sample were retrieved
- MAGs were reconstructed and annotated



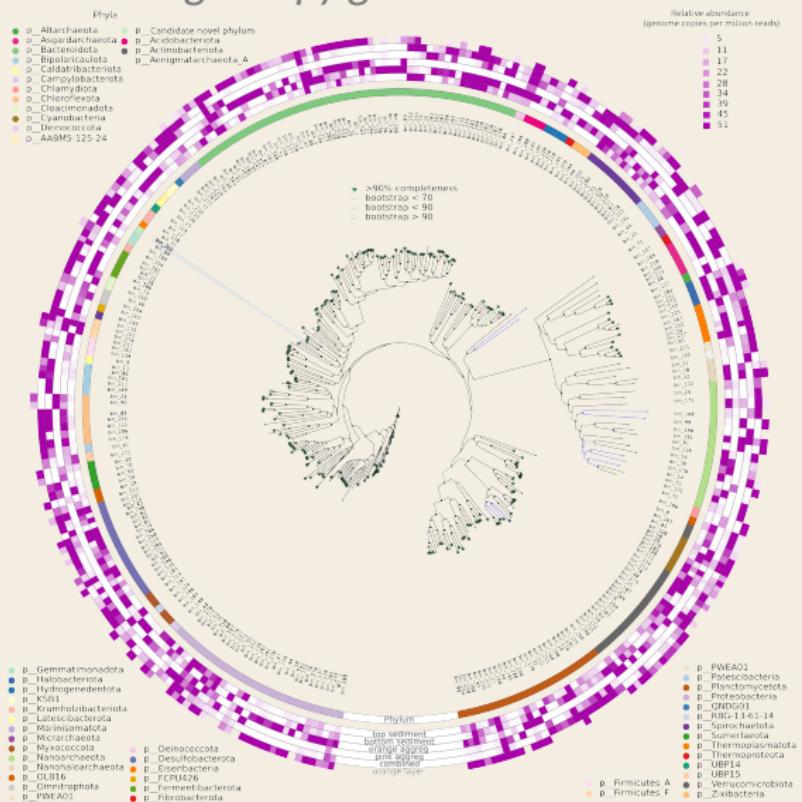
# Amplicon vs metagenomics

*number of phyla retrieved per method*



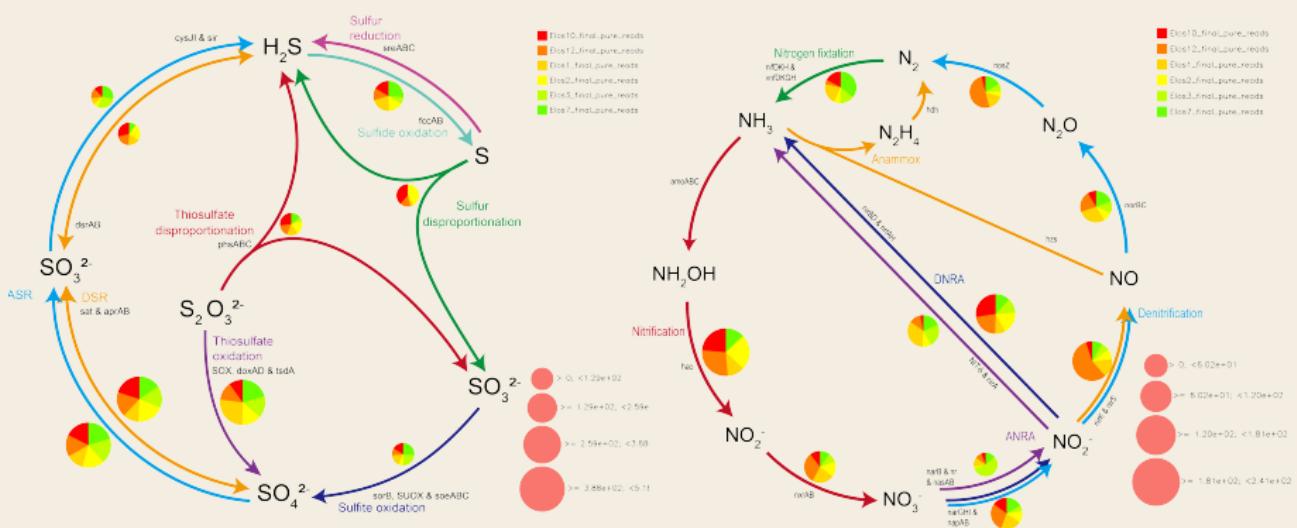
# MAGs phylogeny

based on 25 single-copy genes





# The S and the N cycle using KEGG annotation terms





# Conclusions

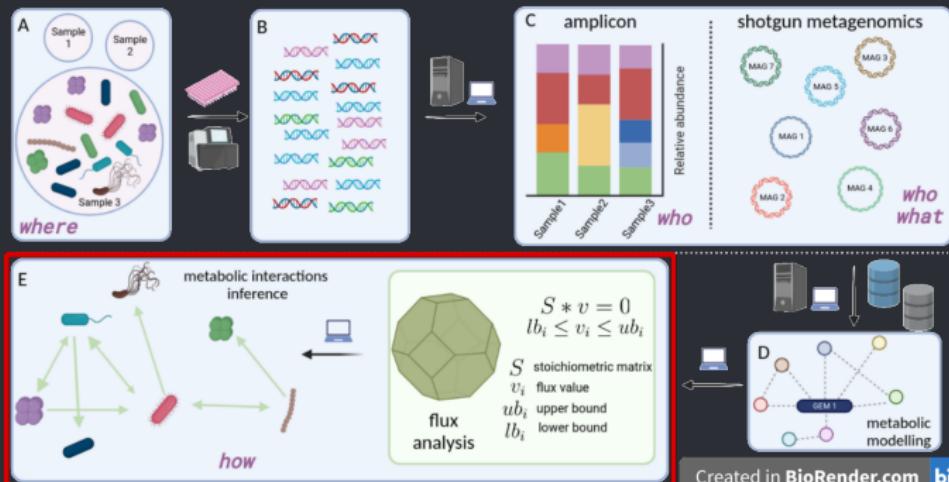
*based on metagenomics analysis in the Tristomo marsh*

- seasonality plays a key-role for the microbial mats under study to survive, ensuring oxygenic photosynthesis for a while
- anaplerotic reactions, that are abundant in our samples, may play an important role in replenishing the intermediates of the TCA cycle
- metabolic modelling can shed further light on the effects of the environmental challenges on the mat construction

## General conclusions

- Bioinformatics approaches enhance microbial diversity assessment based on HTS data
- Containerization technologies and e-infrastructures provide the means for computational capacity and reproducibility
- High quality metadata enable efficient exploitation of sequencing data in a meta-analysis level
- Markov Chain Monte Carlo approaches enable flux sampling in high-dimensional polytopes
- Hypersaline mats host a great range of novel taxa & their functioning might be subject to anaplerotic reactions

# Future perspectives



## A (bit) more holistic framework

*"a combination of quantitative high - throughput experiments and predictive metabolic models can elucidate the genotype - phenotype map of microbial metabolic strategies"* - Bajic and Sanchez (2020)

# Wrap-up

## software tools



a pipeline for eDNA metabarcoding analysis

[github.com/hariszaf/pema](https://github.com/hariszaf/pema)



[github.com/hariszaf/darn](https://github.com/hariszaf/darn)



[github.com/lab42open-team/](https://github.com/lab42open-team/) [github.com/GeomScale/dingo](https://github.com/GeomScale/dingo)

the prego\* repositories



# Publications

- [1] Zafeiropoulos, H., Paragkamian, S., Ninidakis, S., Pavlopoulos, G.A., Jensen, L.J. & Pafilis, E. (2022). PREGO: a literature- and data-mining resource to associate microorganisms, biological processes, and environment types. *Microorganisms* 10(2), 293.
- [2] Zafeiropoulos, H., Gargan, L., Hintikka, S., Pavloudi, C. & Carlsson, J. (2021). The Dark mAtteR iNvestigator (DARN) tool: getting to know the known unknowns in COI amplicon data. *Metabarcoding and Metagenomics*, 5, e69657.
- [3] Polymenakou, P.N., Nomikou, P., Zafeiropoulos, H., ..., Kyrpides, N.C., Kotoulas, G. & Magoulas, A. (2021). The santorini volcanic complex as a valuable source of enzymes for bioenergy. *Energies*, 14(5), p.1414.
- [4] Chalkis, A., Fisikopoulos, V., Tsigaridas, E. & Zafeiropoulos, H. (2021). Geometric algorithms for sampling the flux space of metabolic networks, *37th International Symposium on Computational Geometry (SoCG 2021)*.
- [5] Zafeiropoulos, H., Gioti, A., Ninidakis, S., Potirakis, A., Paragkamian, S., ... & Pafilis, E. (2021). Os and 1s in marine molecular research: a regional HPC perspective. *GigaScience*, 10(8), giab053.
- [6] Zafeiropoulos, H., Viet, H. Q., Vasileiadou, K., Potirakis, A., Arvanitidis, C., Topalis, P., Pavloudi, C. & Pafilis, E. (2020). PEMA: a flexible Pipeline for Environmental DNA Metabarcoding Analysis of the 16S/18S ribosomal RNA, ITS, and COI marker genes. *GigaScience*, 9(3), giaa022.
- [7] Paragkamian, S., Sarafidou, G., ..., Zafeiropoulos, H., Arvanitidis, C., Pafilis, E. & Gerovasileiou, V. Automating the curation process of historical literature on marine biodiversity using text mining: the DECO workflow (*accepted in Frontiers in Marine Science*)
- [8] Pavloudi, C. & Zafeiropoulos, H. (2022) Deciphering the community structure and the functional potential of a hypersaline marsh microbial mat community (*under review at FEMS Microbiology Ecology*)
- [9] Garza, D.R., Gonze, D., Zafeiropoulos, H., Liu, B. & Faust, K., (2022) Metabolic models of human gut microbiota: advances and challenges (*under review at Cell systems*)
- [10] Chalkis, A., Fisikopoulos, V., Tsigaridas, E. & Zafeiropoulos, H. dingo: a Python library for metabolic networks analysis (*under preparation*)

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## My corner:

Would not be here  
if it was not with you.



# Computing infrastructures an alternative for the most!



We will develop a workflow for the analysis of Genomic Observatories (GOs) data that will allow researchers to deal better with the increasing amount of data

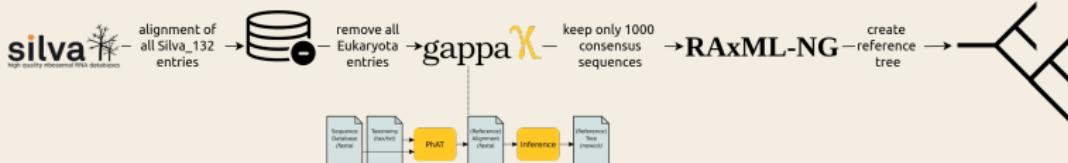




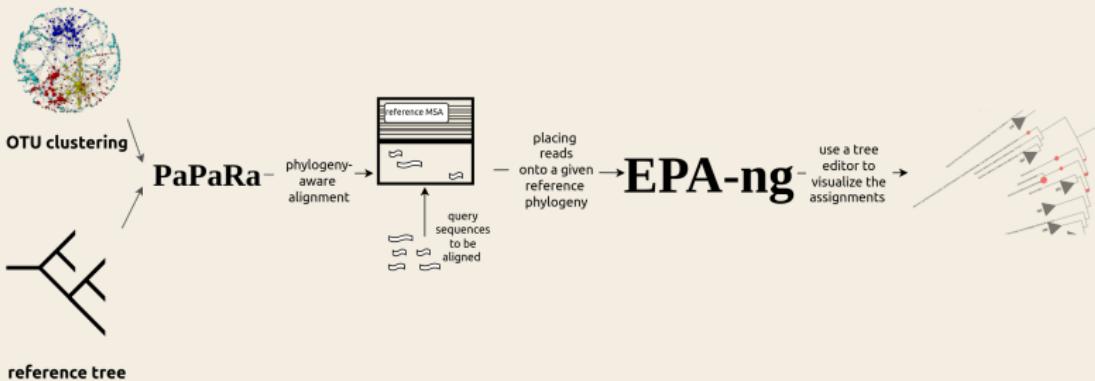
# PEMA features

*phylogeny-based taxonomy assignment for the case of  
16S rRNA gene*

## A. create reference tree



## B. phylogeny-based taxonomy assignment



# A real case hypothesis generation scenario

## *Posidonia and its microbiome*



What about ***Posidonia*** ?

Literature suggests that  
Planctomycetes  
and especially *Blastopirellula*  
and *Rhodopirellula*  
are commonly  
found in its microbiome.

Why so ?

Let us have a look [here!](#)

## Co-mentioning and scoring scheme

which are the most worthy and relevant associations

- genome annotation oriented associations: fixed scores
- associations in the *Environmental Samples* channel are scored based on the number of samples they co-occur.
- similarly, in the *Literature* channel, based on the number of publications

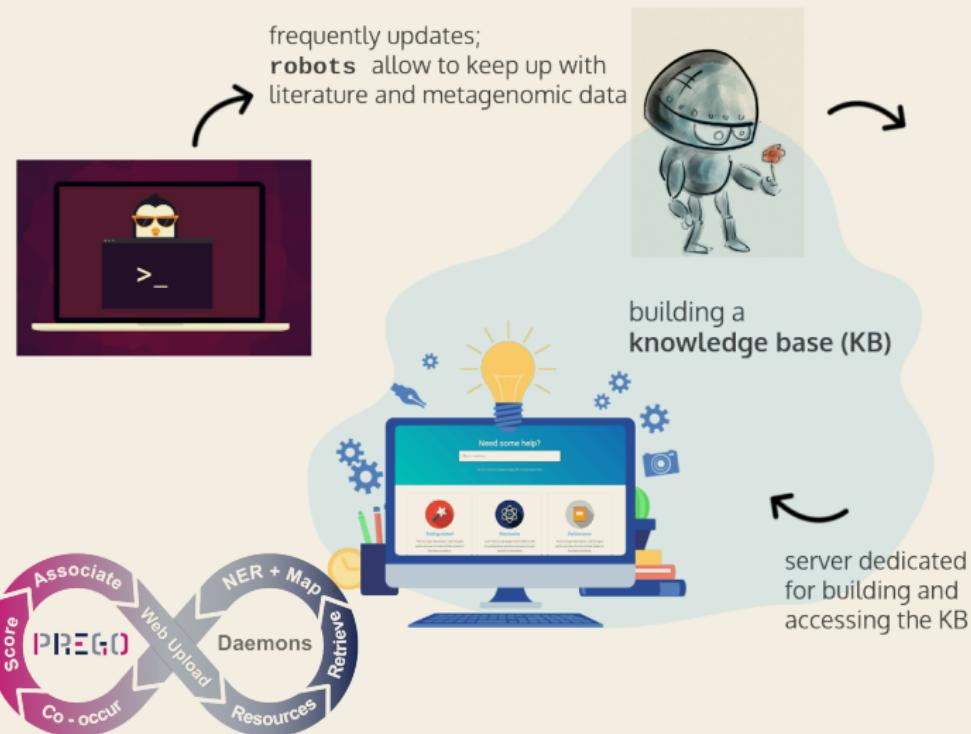
		Y = y		
		Yes	No	Total
X = x	Yes	$c_{x,y}$	$c_{x,0}$	$c_{x..}$
	No	$c_{0,y}$	$c_{0,0}$	$c_{0..}$
	Total	$c_{.,y}$	$c_{.,0}$	$c_{..}$

Environmental samples score:

$$\text{score}_{x,y} = 2.0 * \sqrt{\frac{c_{x,y}}{c_{.,y}}}^a \quad (1)$$

# Building a knowledge-base

*development and information technology operations*



© Thanos Dailianis

## From concentrations to fluxes to study changing environments

We can describe the mass balance of a chemical compound as the difference between the sum of the fluxes of all the reactions that form it and the sum of all that degrade it.

$$\frac{d\omega_i}{dt} = \sum_k s_{ik} v_k = \langle s_i, v \rangle$$

and thus:

$$\frac{d\omega}{dt} = Sv$$

# The region of steady states

*moving to full dimensional polytope*

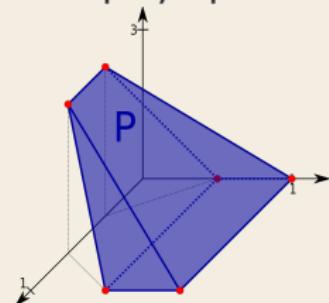
The *constraints* on the reactions fluxes.

$$Sv = 0, \quad (2) \quad v = Nx$$

$$v_{lb} \leq v \leq v_{ub}$$

$$S \in \mathbb{R}^{m \times n}, v \in \mathbb{R}^n$$

As a *full dimensional polytope*



$$P := \{x \in \mathbb{R}^d | Ax \leq b\}$$

$N \in \mathbb{R}^{n \times d}$  denotes the matrix of the null space of  $S$ , i.e.  $SN = 0_{m \times d}$ .

By replacing  $v$  with  $Nx$  in Equation 2, we get the full dimensional polytope  $P$ , where  
 $A = \begin{pmatrix} I_n N \\ -I_n N \end{pmatrix}$  and  $b = \begin{pmatrix} v_{ub} \\ v_{lb} \end{pmatrix} N$ , (in  $\mathbb{R}^d$ ).

## Random walk performance metrics

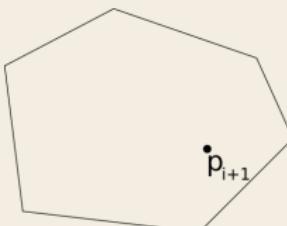
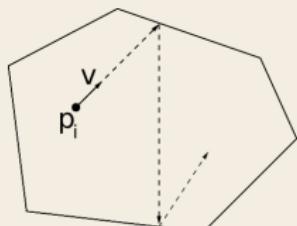
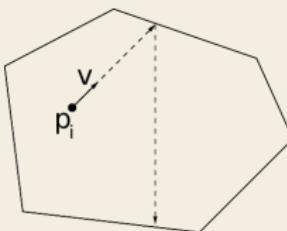
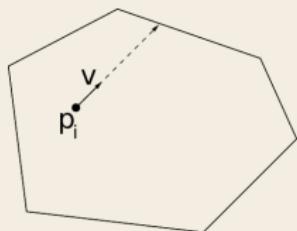
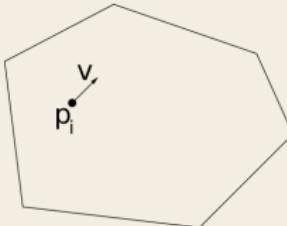
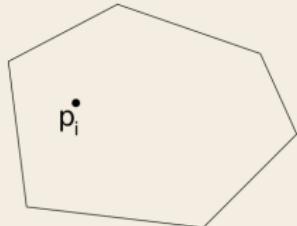
- **cost per iteration:** the number of operations the algorithm needs to sample a single point
- **mixing time:** the number of samples the algorithm needs to burn in order to lose dependency from previous iterations (i.i.d)
- **cost per sample:** the total number of operations the algorithm needs to sample an i.i.d point

## MCMC Convergence diagnostics

- **Effective Sample Size (ESS):**  
the number of effectively independent draws from the target distribution that the Markov chain is equivalent to
- potential scale reduction factor (PSRF)

# Billiard walk

for random sampling



Generate the length of the trajectory  $L \sim D$ .

Pick a uniform direction  $v$  to define the trajectory.

The trajectory reflects on the boundary if necessary.

Return the end of the trajectory as  $p_i + 1$ .

# Find possible targets against SARS-CoV-2

## *a flux sampling application*

*Bioinformatics*, 36(26), 2020, i813–i821

doi: 10.1093/bioinformatics/btaa813

ECCB2020

OXFORD

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Systems

## **FBA reveals guanylate kinase as a potential target for antiviral therapies against SARS-CoV-2**

**Alina Renz<sup>1,2,\*</sup>, Lina Widerspick<sup>1</sup> and Andreas Dräger<sup>1,2,3,\*</sup>**

<sup>1</sup>Computational Systems Biology of Infections and Antimicrobial-Resistant Pathogens, Institute for Bioinformatics and Medical Informatics (IBMI) and <sup>2</sup>Department of Computer Science, University of Tübingen, Tübingen 72076, Germany and <sup>3</sup>German Center for Infection Research (DZIF), partner site Tübingen, Germany

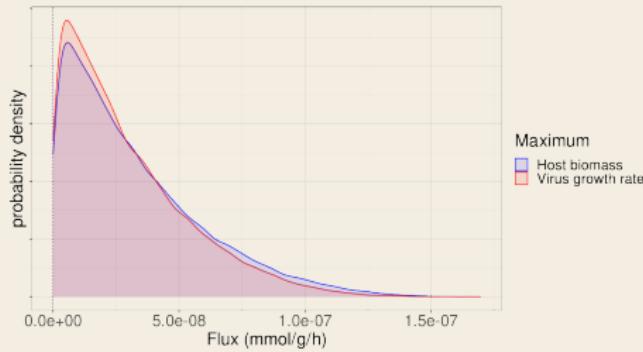
- Renz et al. '20 built the biomass function of Sars-Cov-2 to build a host - virus network
- Using FBA they computed an optimal steady state using
  - (i) human biomass maintenance,
  - (ii) virus growth rate
- They found reaction GK1 as a possible anti-viral target.

# Find possible targets against SARS-CoV-2

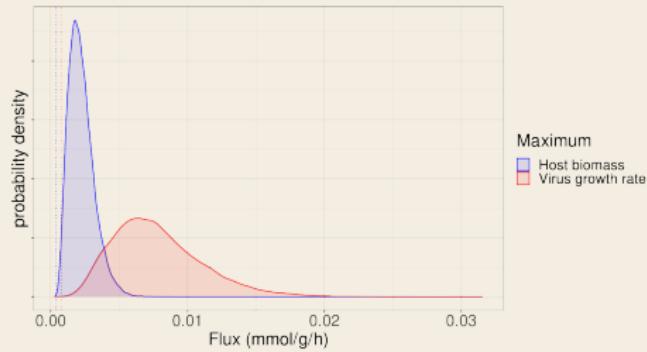
## *a flux sampling application*



Reaction TYMSULT



Reaction GK1



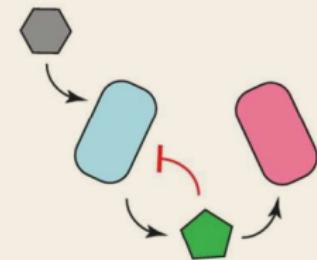
- Check if the flux distribution of a reaction changes.
- Find possible anti-viral targets and study further.

For more about this example case, you may check this [blog-post](#).

## Further applications of metabolic flux sampling



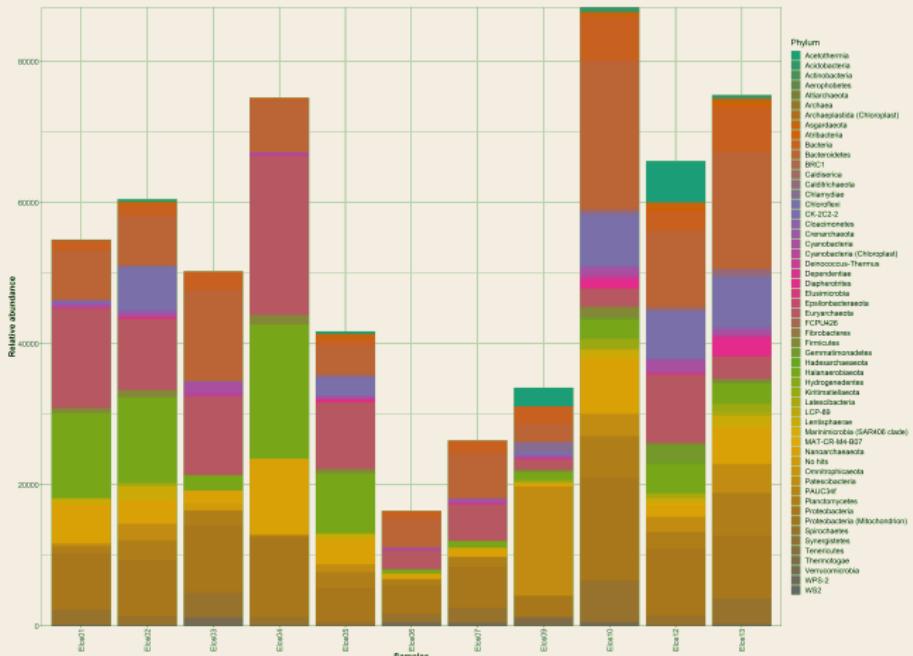
Scott, William T., et al. "Metabolic flux sampling predicts strain-dependent differences related to aroma production among commercial wine yeasts." Microbial cell factories 20.1 (2021): 1-15.



What about microbial interactions ?



# Abundances of the main microbial taxa, at the phylum level based on 16S rRNA amplicon data



## Metabolic pathways per biogeochemical cycle and their relative abundance at each sample

