IDEFIX as a modelling basis for community ecology

Background, concept & nascent projects

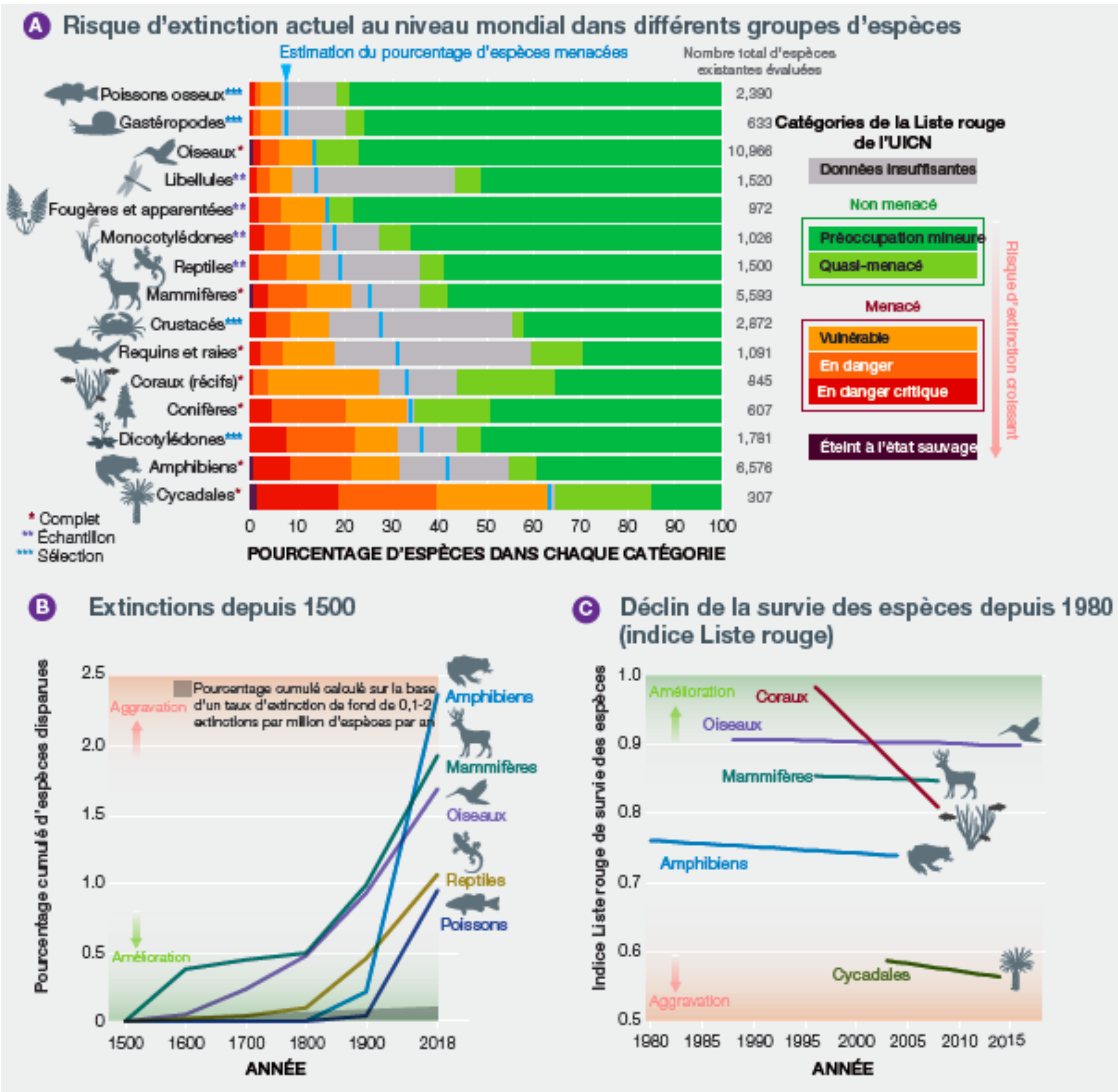
François Rincon

Le déclin : Quelques chiffres

Séminaire P. Grandcolas, directeur adjoint INEE

Science and Policy for People and Nature

Un million d'espèces en risque d'extinction en quelques décennies



Dans le monde :

1/3 des espèces de vertébrés en fort danger d'extinction d'ici 2040

7% des mollusques du monde déjà disparus

En France ou en Europe :

Baisse moyenne des populations d'oiseaux en France : 1/3 en 30 ans

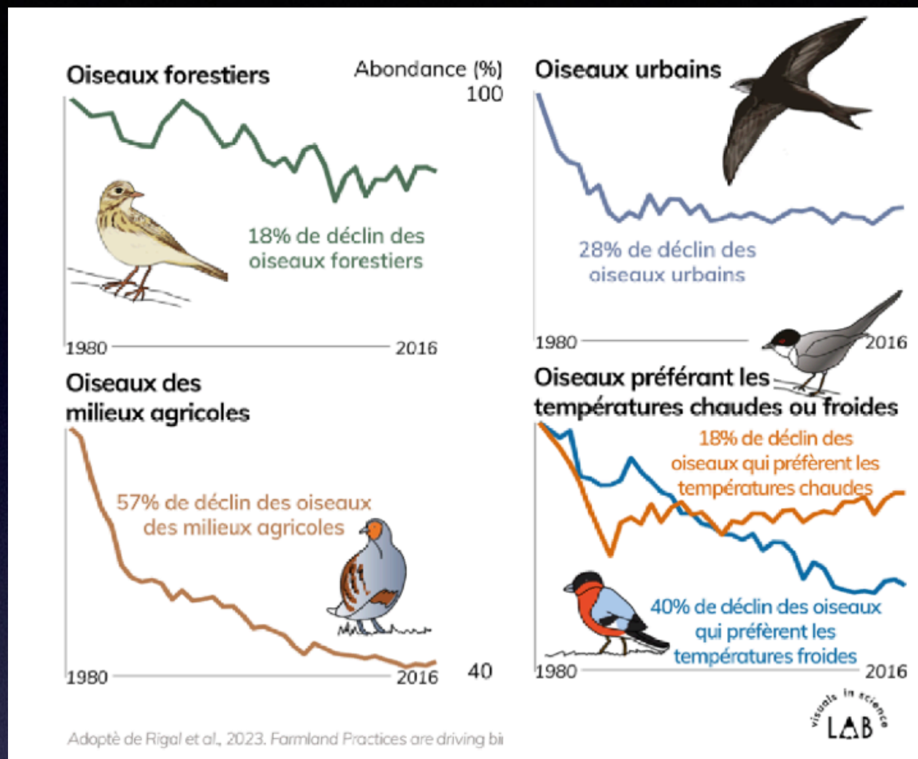
Baisse moyenne de +70% des populations d'insectes en Europe en 10 ans

42% des 454 espèces d'arbres en danger d'extinction en Europe

UK Farmland Birds. 55% decline 1970 – 2019

From biodiversitystripes.info Data: Indicator C5 – Birds of the wider countryside – Farmland birds. Department for Environment, Food and Rural Affairs, UK. 2021. UK Biodiversity Indicators 2021. Contains public sector information from Defra, licenced under the Open Government Licence v3.0

The times we are living in

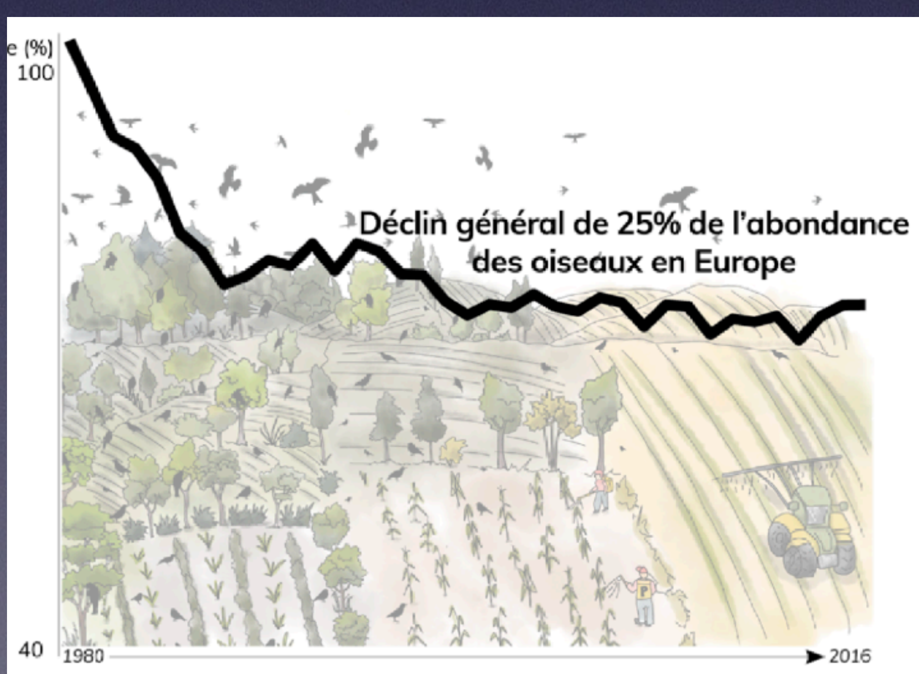


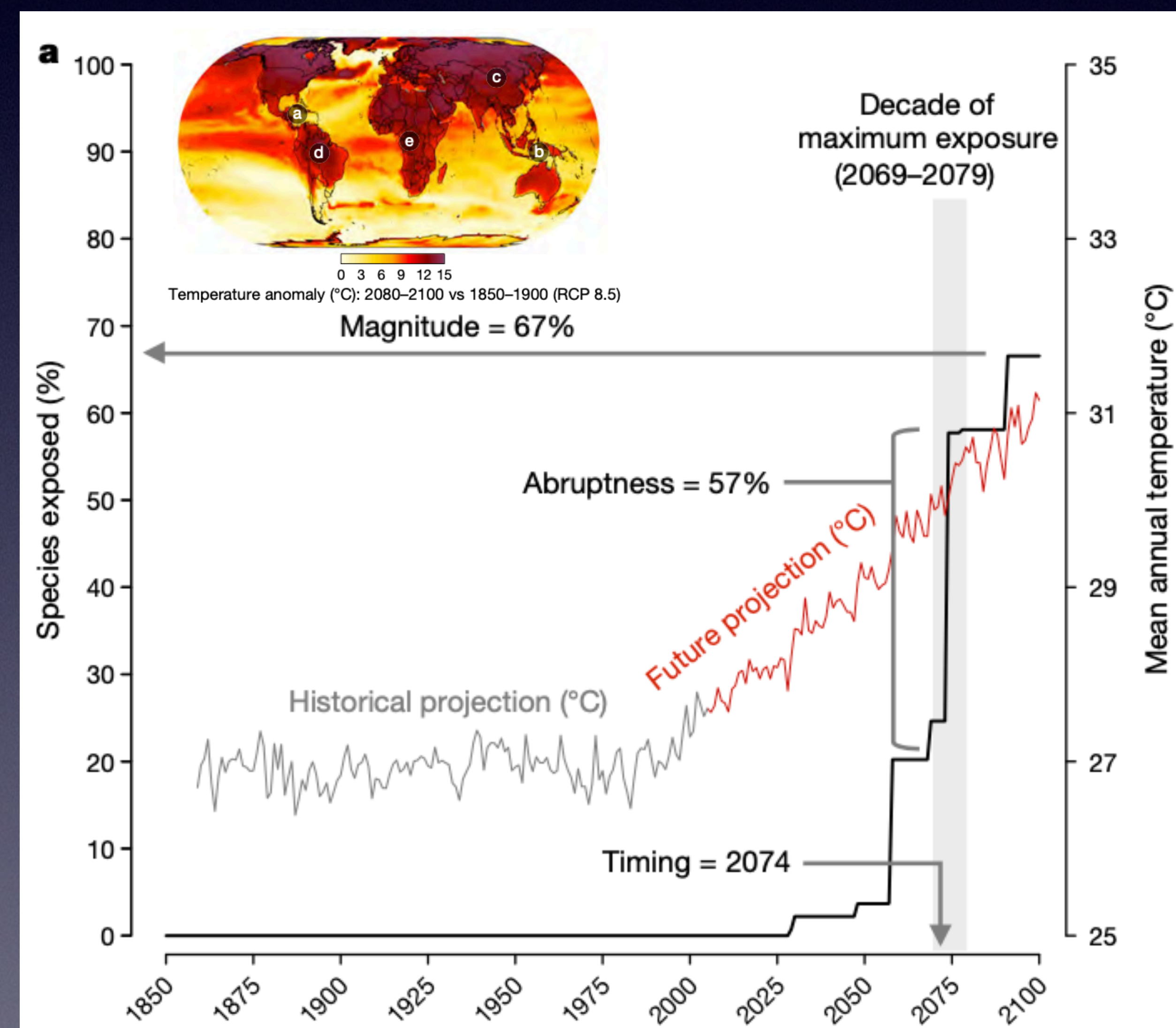
Devictor et al, PNAS 2023

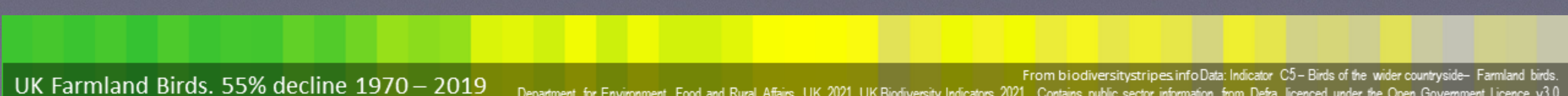
Déclin des abondances de différents groupes dans le temps

L'intensification des pratiques agricoles et l'augmentation des températures sont les principales pressions qui affectent négativement la plupart des populations

[Trisos et al., Nature 2020]







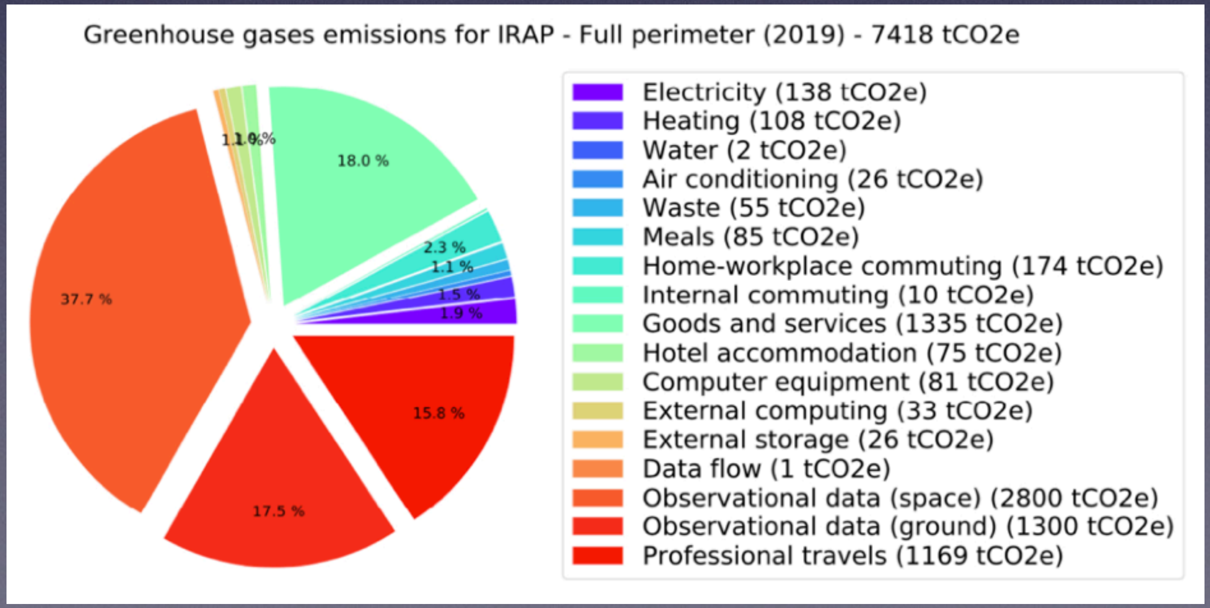
Astronomy and HPC carbon footprint

- Astronomy's astronomical emissions ~40 tCO2eq / yr / astronomer
  - Biggest share = observational infrastructure
- Sustainable future (1.5-2^{o}) ~ 2 tCO2 / yr / human max [IPCC reports]

A lot of emissions for a luxury research activity with no particular urgency

Knödlseder et al., Nature Astron. 2021, 2024

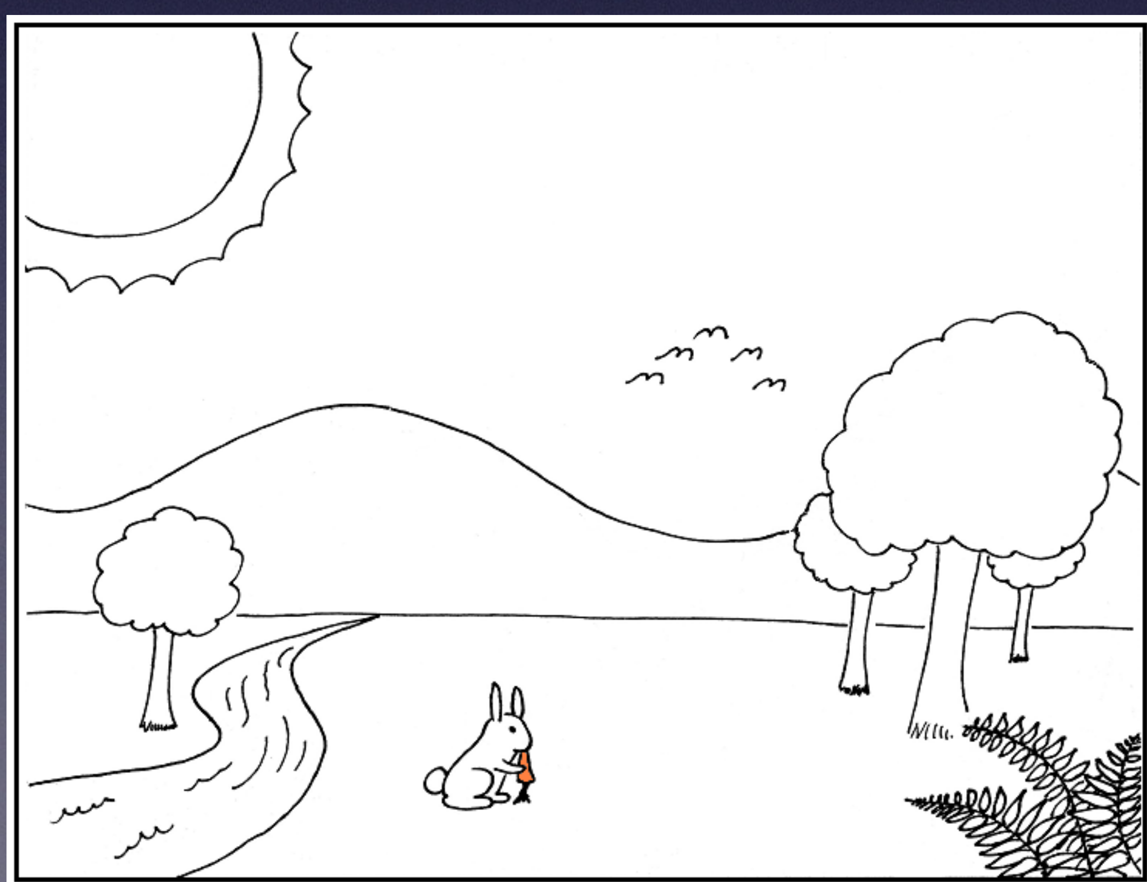
Martin et al., arXiv:2204.12362, 2022

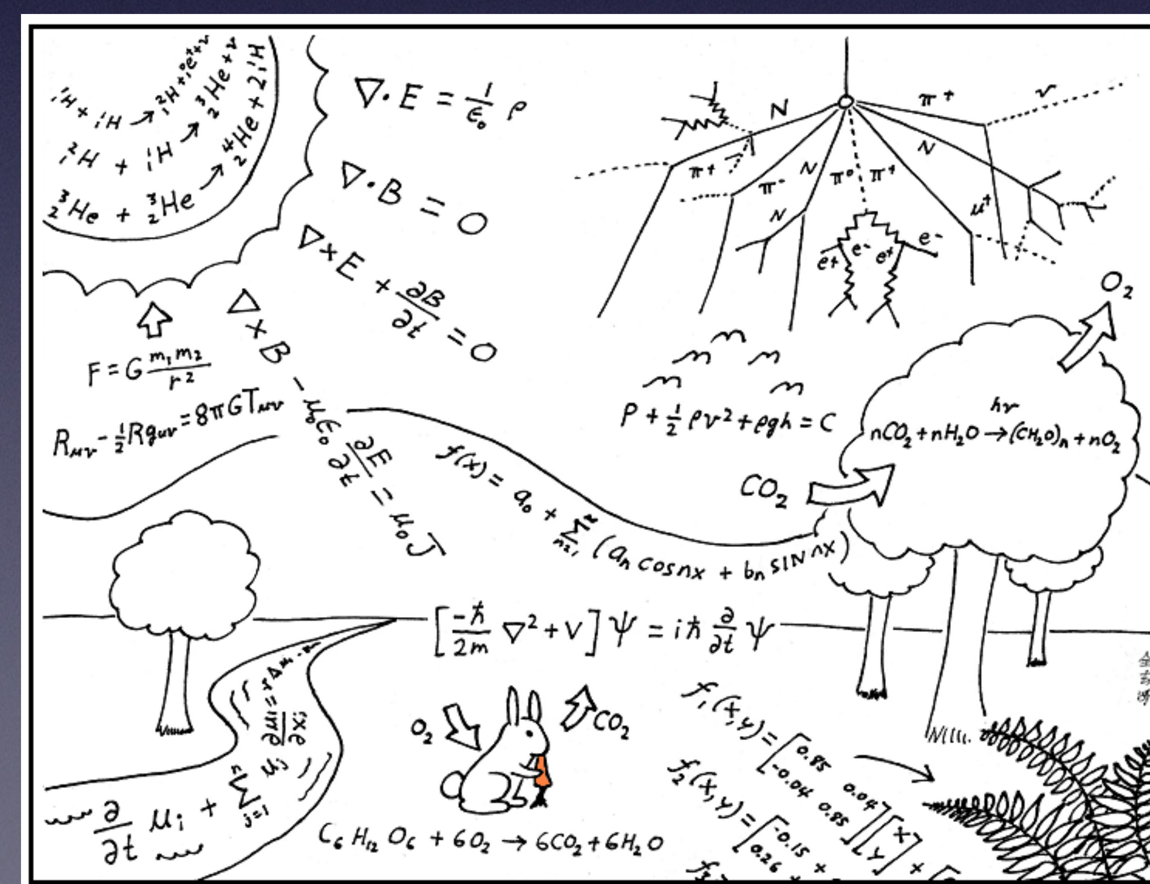


Can (astro)physicists actually be useful to anything ?

“Certains chercheurs pourraient s’engager dans des changements thématiques avec ce type de motivation. Les projets de reconversion thématiques depuis des secteurs à forte empreinte environnementale vers des secteurs où elle est plus faible doivent être accompagnés. De telles reconversions pourraient bénéficier à certains domaines couverts par l’INSU (climat, environnement) tout en étant possiblement problématiques pour d’autres (astrophysique, planétologie).”

Prospective CS INSU 2023 [section IV.D]





From astro to ecological complexity

Understanding key aspects of ecosystemic dynamics and response to anthropogenic pressures is critical & urgent to help mitigate the biodiversity crisis

- Ecosystems are complex dynamical systems
  - Nonlinear, multiscale biotic and abiotic (species-environment) interactions
  - Large number of degrees of freedom (spatio-temporal, multispecies & multitrophic, eco-evolutionary)
- Fundamental questions & problems
  - Stability: what is the nature of upcoming transitions ? Tipping points or gradual, disordered, gradual transition ?
  - Spatio-temporal dynamics: spatial-fragmentation and dispersion effects in the context of climate change
  - “Theory-conservation” gap: should inform biological conservation policies & schemes
- Collaboration with the SETE (CNRS, Ariège) initiated in 2023
  - Interdisciplinary lab (from biology to social sciences & maths)
  - Big interest for theoretical activities and expanding in numerical modelling

Fluid dynamics to the rescue ?

- Fluid dynamics *for* ecosystems

Contents lists available at ScienceDirect

Progress in Oceanography

journal homepage: www.elsevier.com/locate/pocean

ELSEVIER

Lagrangian flow effects on phytoplankton abundance and composition along filament-like structures

Ismael Hernández-Carrasco [a,*], Eva Alou-Font [b], Pierre-Antoine Dumont [c], Andrea Cabornero [b], John Allen [b], Alejandro Orfila [a]

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Observational characterisation of large-scale transport and horizontal turbulent diffusivity in the quiet Sun

F. Rincon[1,2], P. Barrère[1,2,3], and T. Roudier[1,2]

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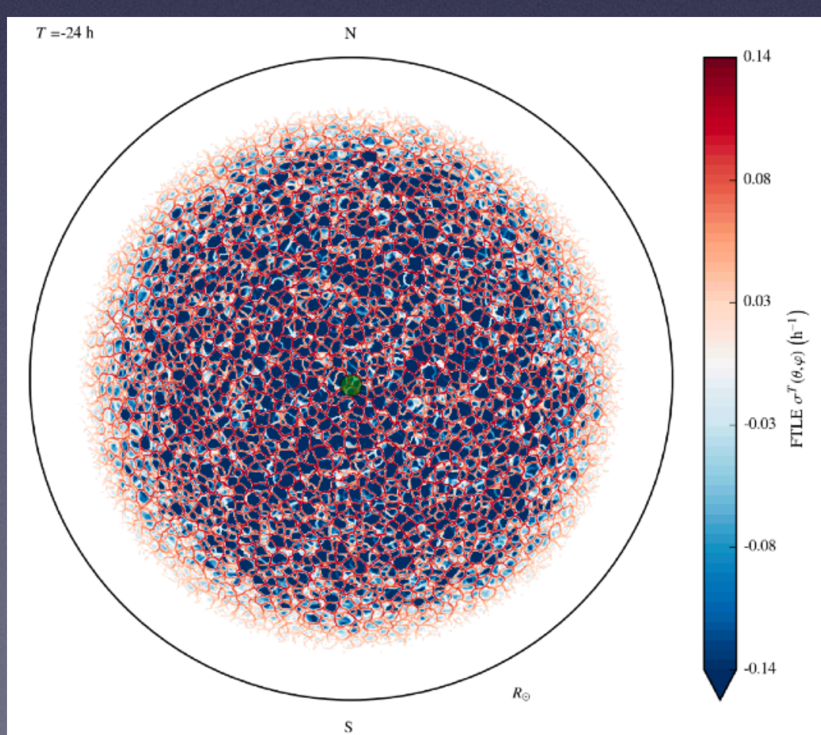
e-mail: frincon@irap.omp.eu

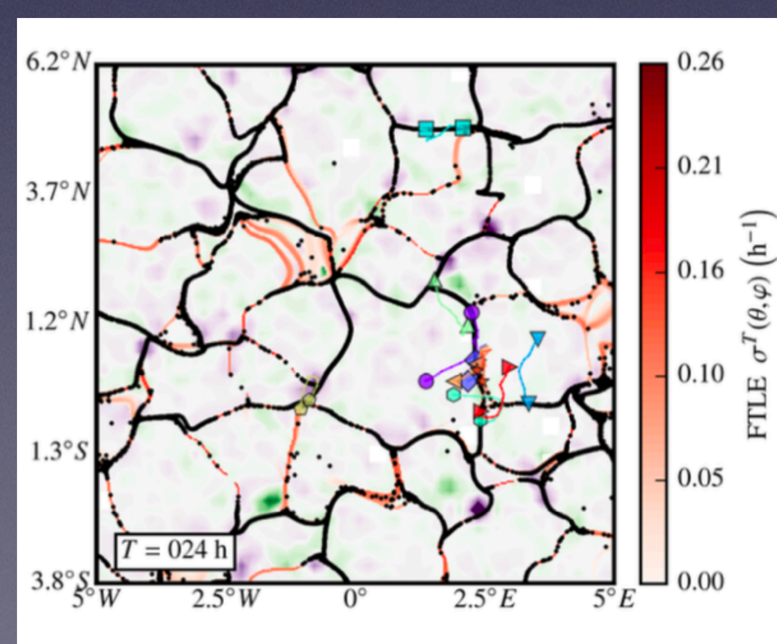
April 22, 2024

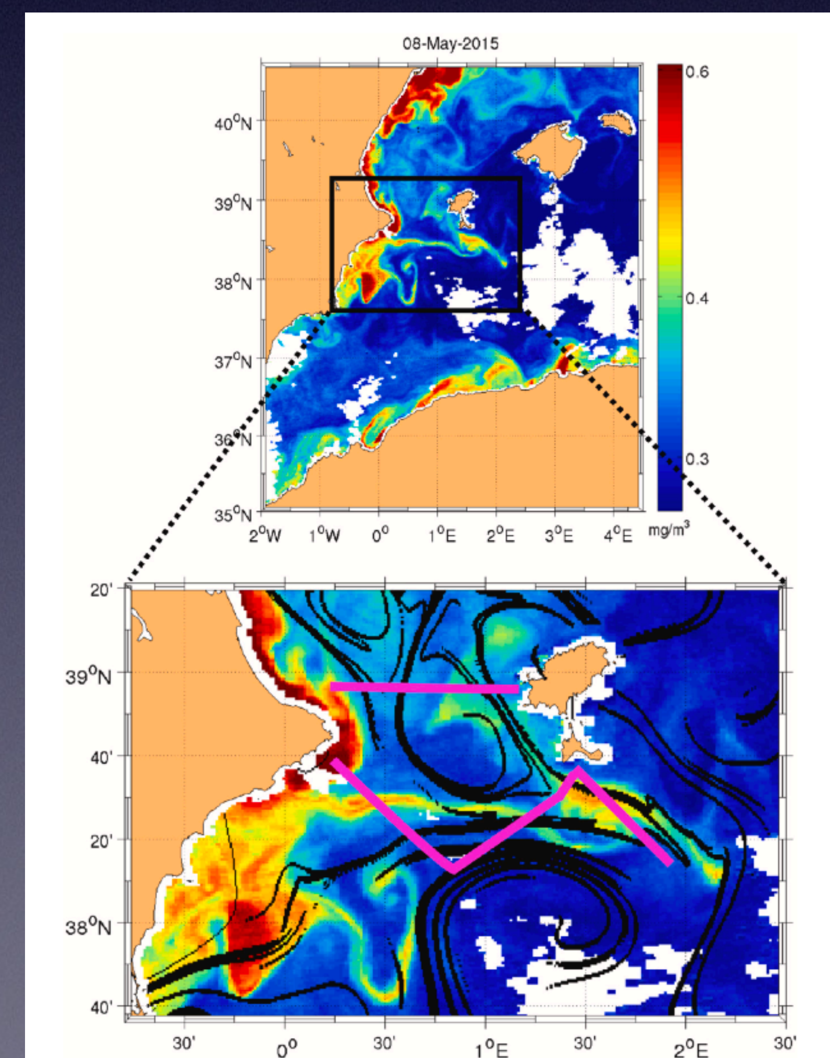
ABSTRACT

The Sun is a magnetic star, and the only spatio-temporally resolved astrophysical system displaying turbulent magnetohydrodynamic thermal convection. This makes it a privileged object of study to understand fluid turbulence in extreme regimes and its interactions with magnetic fields. Global analyses of high-resolution solar observations provided by the NASA Solar Dynamics Observatory (SDO) can shed light on the physical processes underlying large-scale emergent phenomena such as the solar dynamo cycle. Combining a Coherent Structure Tracking reconstruction of photospheric flows, based on photometric data, and a statistical analysis of virtual passive tracers trajectories advected by these flows, we characterise one of the most important such processes, turbulent diffusion, over an unprecedentedly long monitoring period of six consecutive days of a significant fraction of the solar disc. We first confirm, and provide a new global view of the emergence of a remarkable dynamical pattern of Lagrangian Coherent Structures tiling the entire surface. These structures act as transport barriers on the time and spatial scale of supergranulation and, by transiently accumulating



arXiv:2404.14383 submitted





Fluid dynamics to the rescue ?

- Fluid dynamics *of* ecosystems
  - Lotka-Volterra equations of population dynamics

$$\frac{dn_i}{dt} = r_i n_i - D_i n_i^2 - A_{ij} n_i n_j$$

  - Simple spatio-temporal extension

$$\frac{\partial n_i}{\partial t} + \mathbf{v} \cdot \nabla\, n_i = r_i[T, N, C(\mathbf{x}, t)]\, n_i - D_i n_i^2 - A_{ij}(\mathbf{x}, t)\, n_i n_j + \lambda_i \Delta n_i + S_i$$

$$\frac{\partial \{T, N, C\}}{\partial t} + \mathbf{v} \cdot \nabla\, \{T, N, C\} = NL\left(\{n_i\}\right) + \lambda_{\{T,N,C\}}\, \Delta\, \{T, N, C\} + S_{\{T,N,C\}}$$

A massive "multifluid" with many time & spatial scales !

Does any of this make sense ? Well, possibly…

nature ecology & evolution
ARTICLES
https://doi.org/10.1038/s41559-021-01644-4

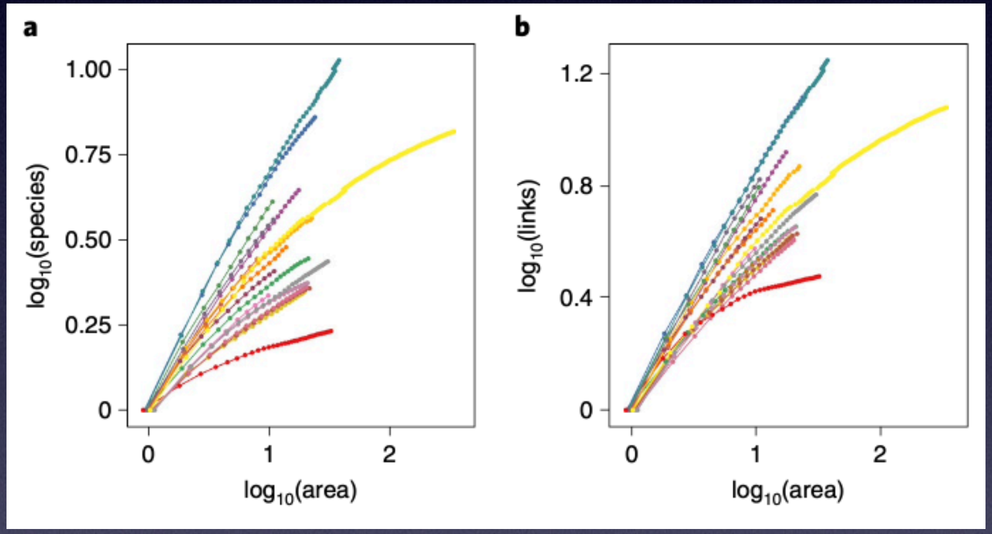
Ecological network complexity scales with area

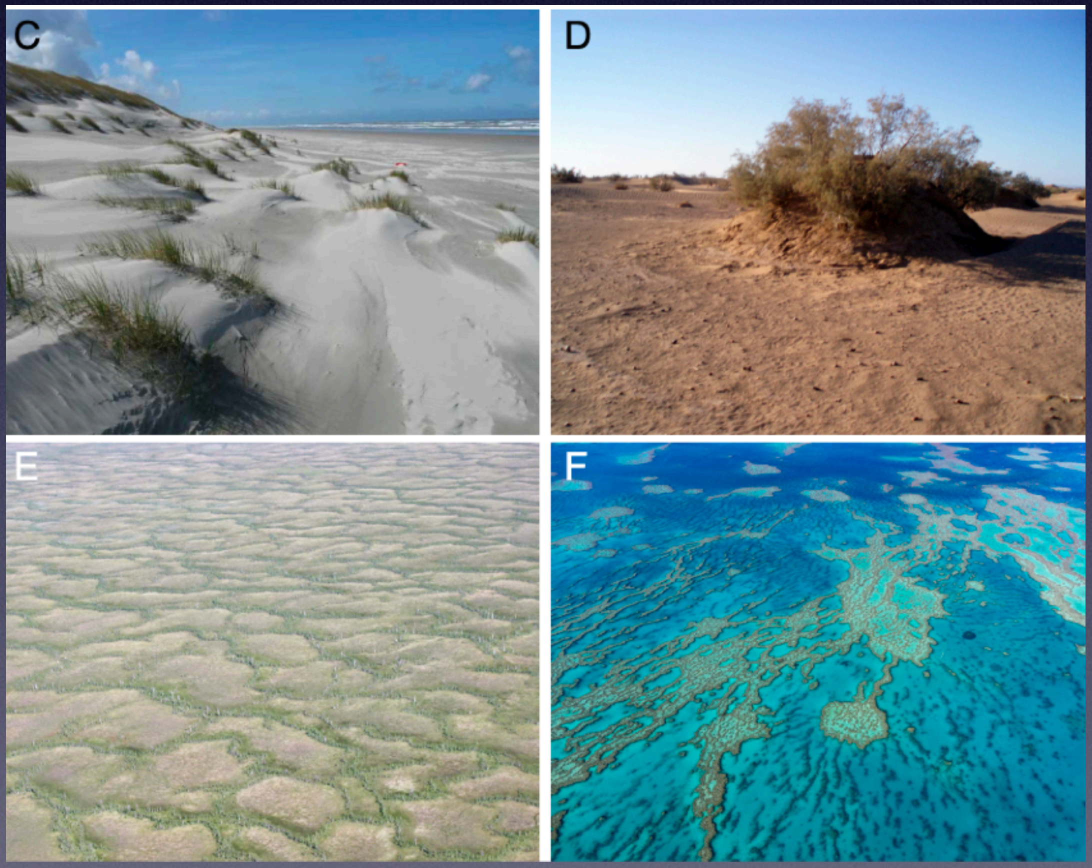
PERSPECTIVE
https://doi.org/10.1038/s41559-018-0517-3
nature ecology & evolution

The spatial scaling of species interaction networks

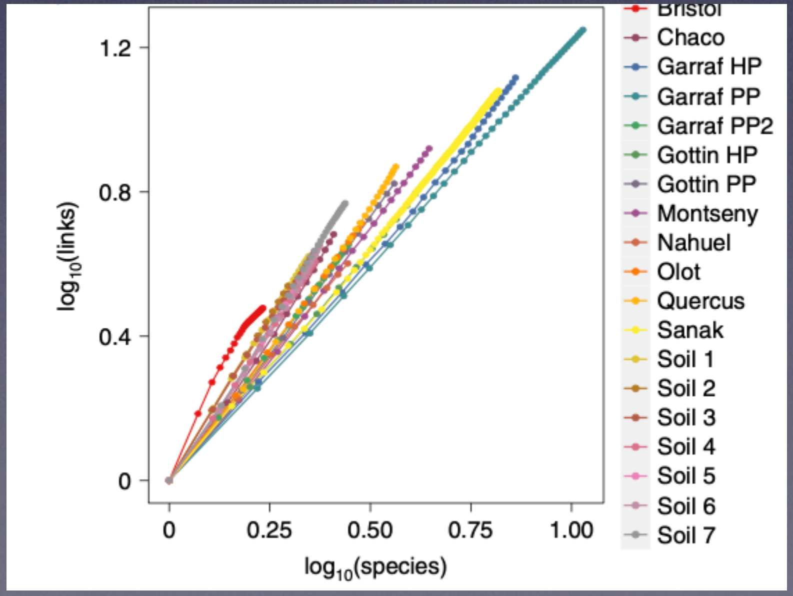
PNAS RESEARCH ARTICLE | ECOLOGY OPEN ACCESS

Phase-separation physics underlies new theory for the resilience of patchy ecosystems



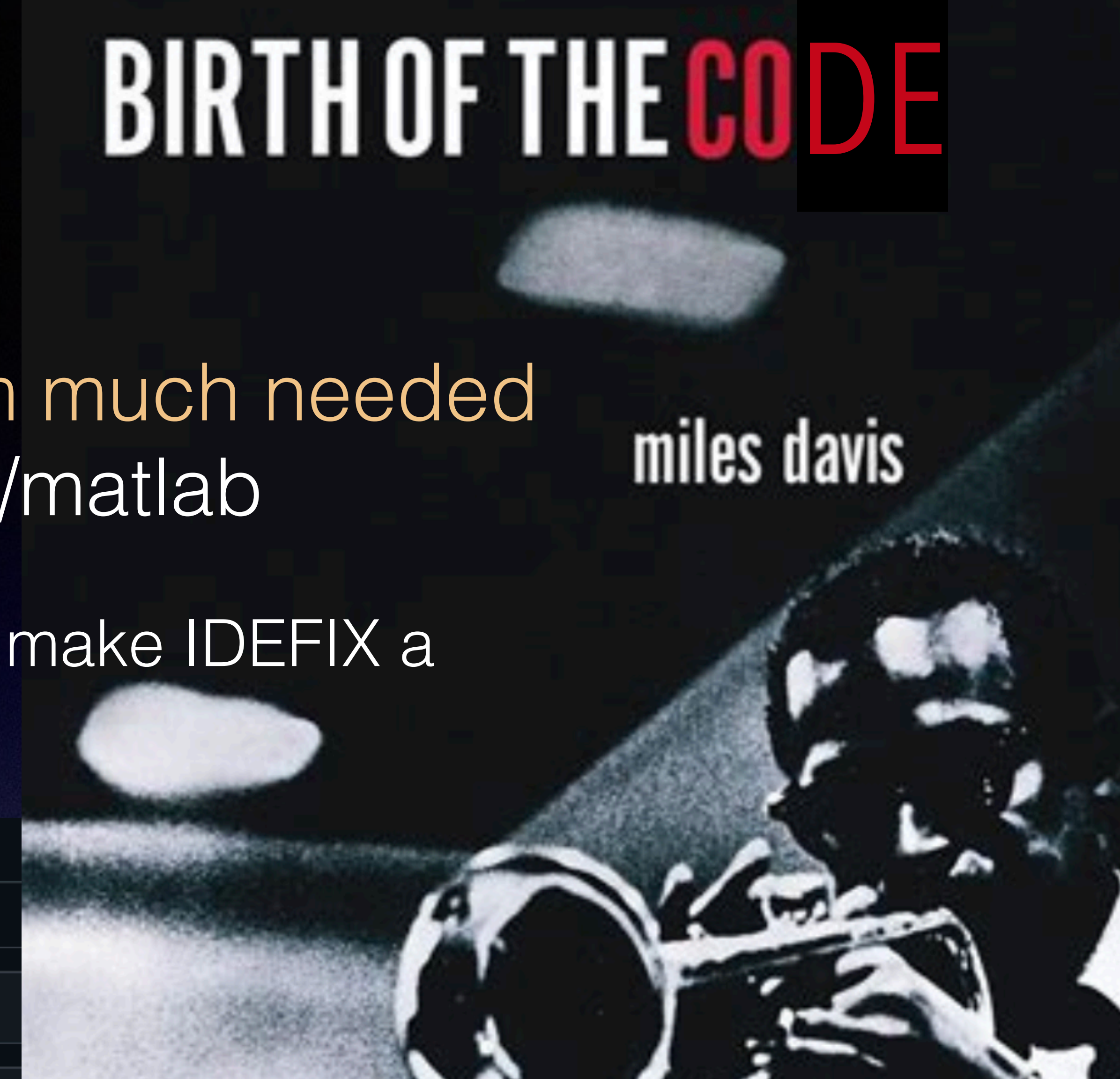


Siteur et al., PNAS 2022



Galiana et al., Nature EE 2018,22

Why am I here ?



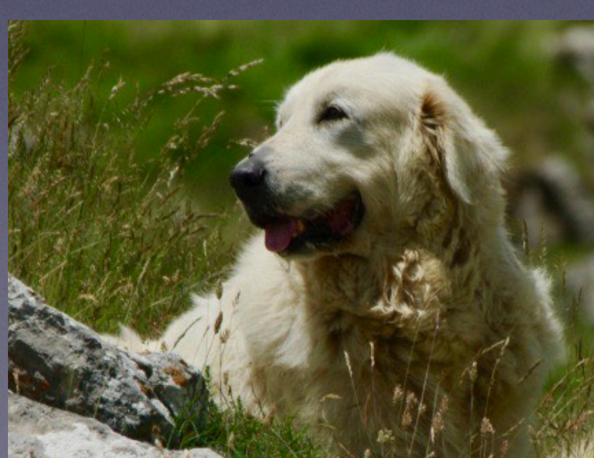
- HPC, code versatility & parallelism much needed in this context — ecologists use R/matlab
  - Geo & I started some work last year to make IDEFIX a cool tool for this kind of problems

patou / src /

rinconirap -Changed the base ecology class stuff to accomodate nSpecies and (opt...

This branch is 48 commits ahead of `master` .

Name	Last commit message	Last commit date
..		
dataBlock	Merge branch 'master' into ecoRincon	4 months ago
ecology	-Changed the base ecology class stuff to accomodate nSpecies and (opt...	3 days ago
fluid	V2.0.05 (#231)	6 months ago
gravity	V2.0.02 (#209)	10 months ago



```
[cabardes][/Users/francoisrincon/patou/patou/src] ls
CMakeLists.txt     global.cpp     idefix.hpp          macros.hpp     profiler.hpp          timeIntegrator.hpp
arrays.hpp         global.hpp     input.cpp           main.cpp       real_types.hpp        utils
dataBlock          gravity        input.hpp           mpi.cpp        reduce.hpp            version.hpp
ecology            grid.cpp       kokkos              mpi.hpp        rkl
error.cpp          grid.hpp       kokkos_types.h      output         setup.cpp
error.hpp          gridHost.cpp   license_header.txt  physics.hpp    setup.hpp
fluid              gridHost.hpp   loop.hpp            profiler.cpp   timeIntegrator.cpp
[cabardes][/Users/francoisrincon/patou/patou/src] cd ecology/
[cabardes][/Users/francoisrincon/patou/patou/src/ecology] ls
CMakeLists.txt  calcflux.hpp   calcrhs.hpp   ecoboundary.cpp ecoboundary.hpp ecology.cpp   ecology.hpp
[cabardes][/Users/francoisrincon/patou/patou/src/ecology]
```

What we need

- Start with spatial version of Lotka-Volterra

(Nspecies,N_x,N_y,N_z) 4D Idefix array field

Species-dependent spatial diffusion

$$\frac{\partial n_i}{\partial t} + \mathbf{v} \cdot \nabla n_i = r_i[T, N, C(\mathbf{x}, t)]\, n_i - D_i n_i^2 - A_{ij}(\mathbf{x}, t)\, n_i n_j + \lambda_i \Delta n_i + S_i$$

Time-integrator

Advection

Space-dependent growth-rate & autotrophic saturation matrices (4D)

Source/sink terms

Trickiest bit: 5D heterotrophic interaction matrix

```
idefix_for("Interactions", 0, nSpeciesAbiotic, 0, nSpeciesAbiotic, data->beg[KDIR], data->end[KDIR],
                              data->beg[JDIR], data->end[JDIR],
                              data->beg[IDIR], data->end[IDIR],
         KOKKOS_LAMBDA(const int s, const int sprime, const int k, const int j, const int i) {

      // Lotka-Volterra Interaction coefficients
       if(haveASpatialfunc)  spN(s,k,j,i) -= dt*(ASpatialArray(s, sprime, k, j, i))*sp(sprime,k,j,i)*sp(s,k,j,i);
       if(haveAfunc)  spN(s,k,j,i) -= dt*(AArray(s,sprime))*sp(sprime,k,j,i)*sp(s,k,j,i);

    });
```

- Abiotic/environmental fields incorporated as species

Kelp, lobsters and urchins

- A simple test-problem for the code

Predation by urchins

Kelp
$$\frac{\partial K}{\partial t} = r_K K - D_K K^2 - A_{KU} K U$$

Feeding on kelp

Predation by lobsters

Urchins
$$\frac{\partial U}{\partial t} = r_U(T) U - D_U U^2 - A_{UK} U K - A_{UL} U L$$

T-dependent growth

Lobsters
$$\frac{\partial L}{\partial t} = -D_L L^2 - A_{LK} L K - A_{LU} L U + S_L$$

Lobsters benefit from kelp & feed on urchins

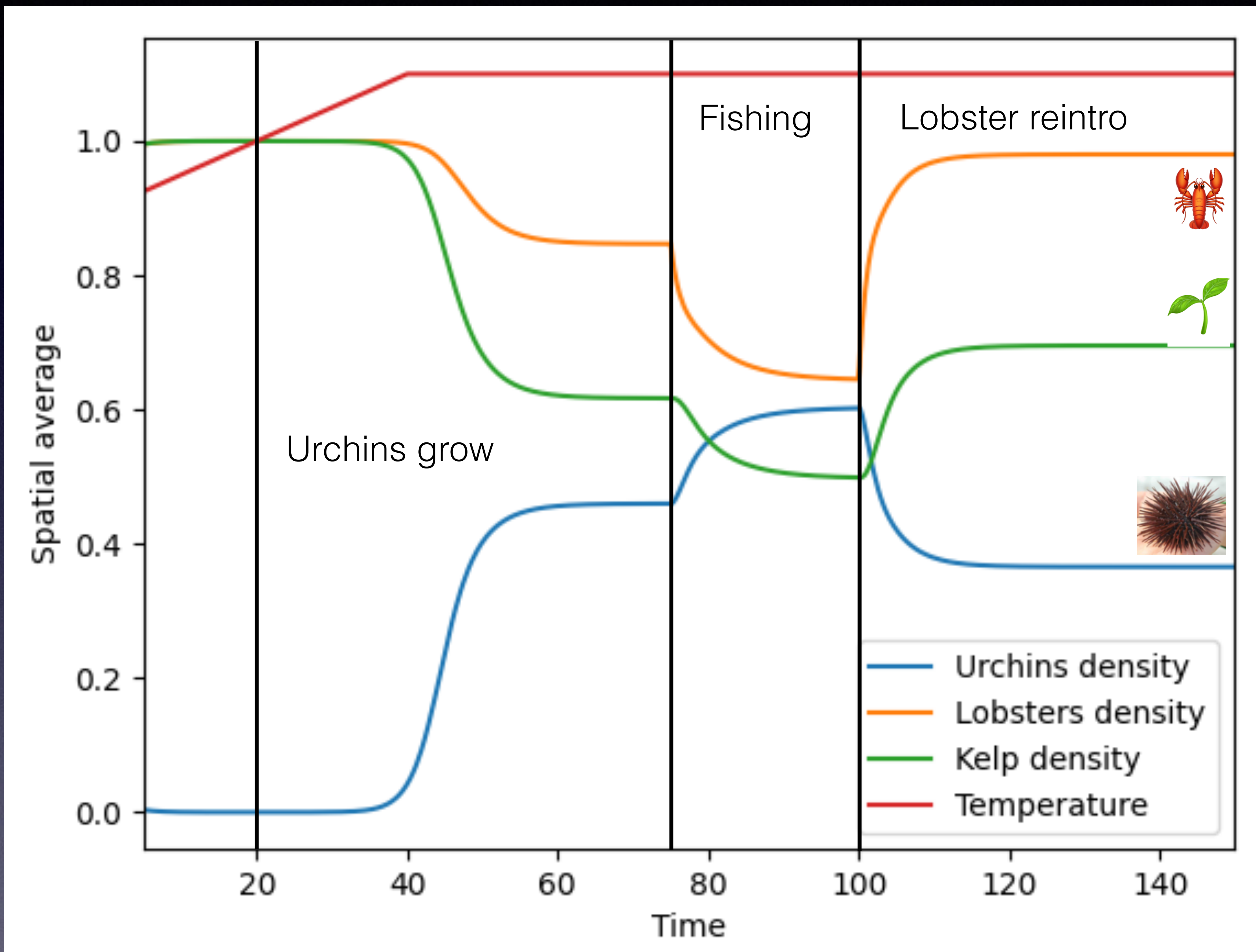
Fishing / Reintroduction

Temperature
$$\frac{\partial T}{\partial t} = S_T$$

Ocean warming

Parmesan et al., Ecol. Lett. 2013

Kelp, lobsters and urchins



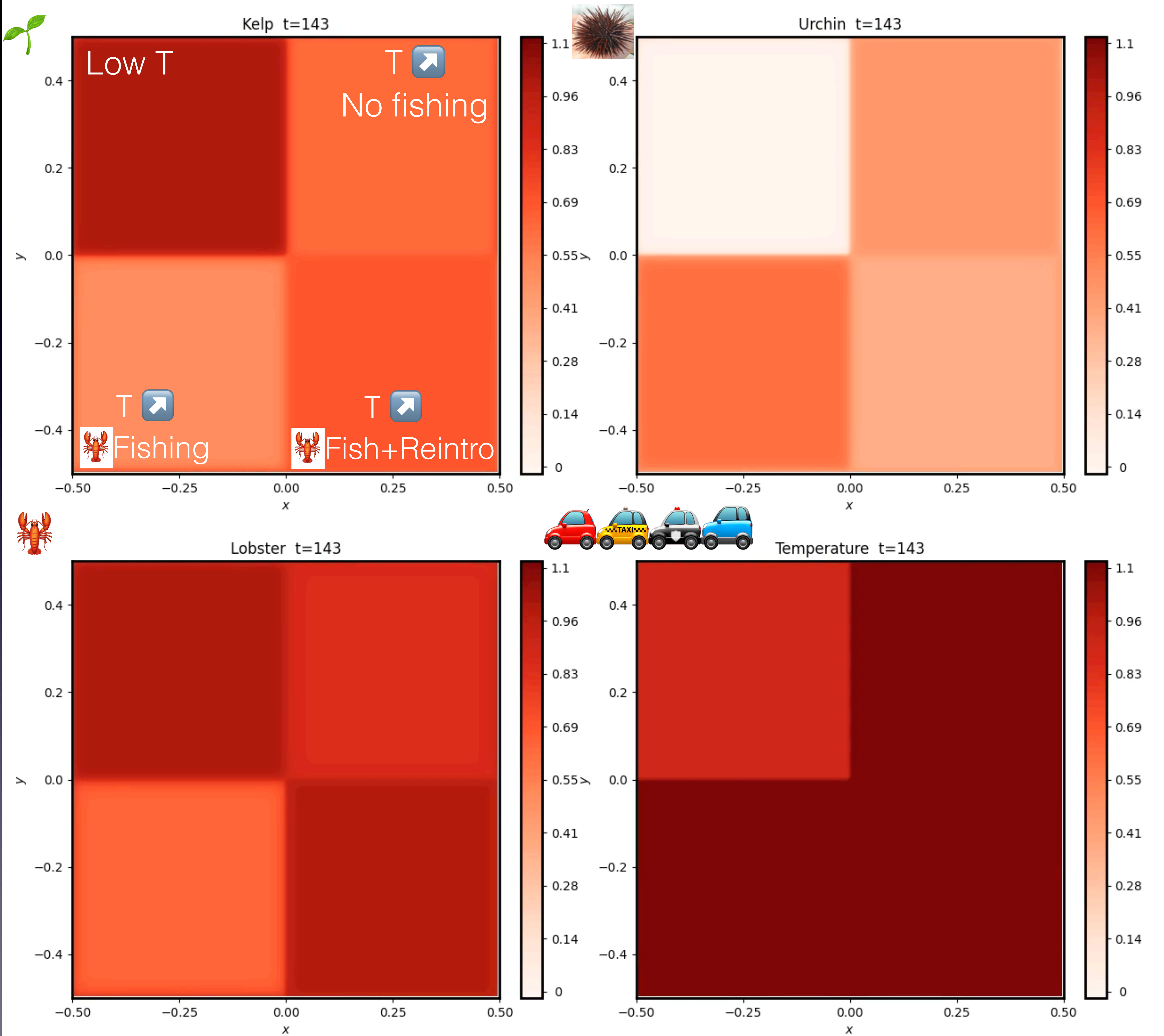
Parmesan et al., Ecol. Lett. 2013

BOX 2 Conservation case study: Kelp and climate change

Here, we present a case study of impacts of climate change on giant kelp *Macrocystis pyrifera* forests in eastern Tasmania (southeast Australia). This case study of climate change, invasion, interactions and adaptation illustrates many of the recommendations we make here. Recent changes in these kelp forests demonstrate how the complexity of natural systems can limit the validity of simple attribution studies and highlights the need to move beyond attribution.

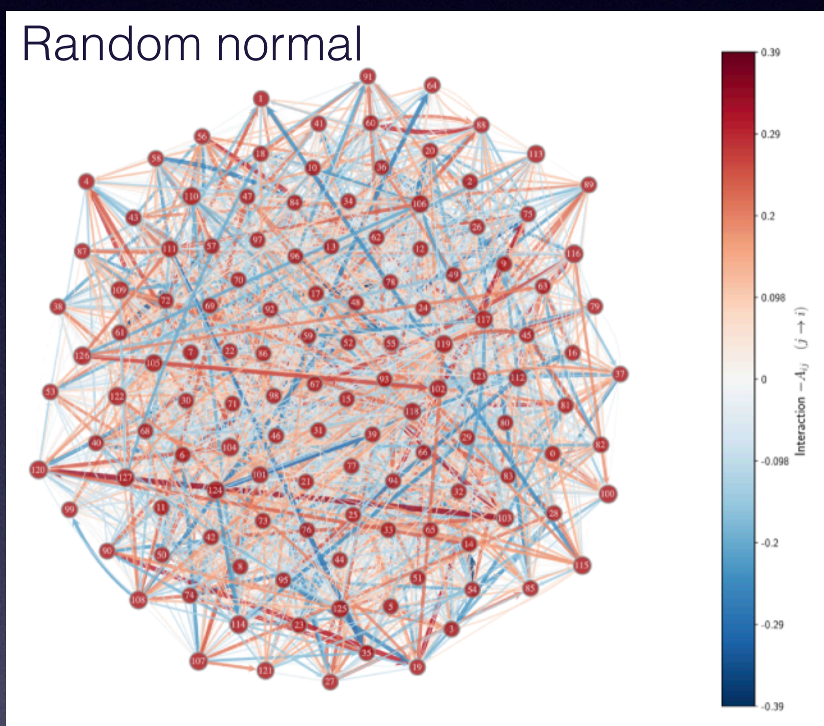
Historically, there have been dense giant kelp forests in the region. These have supported a rich ecosystem, including abundant predatory rock lobsters *Jasus edwardsii* that have kept the abundance of sea urchins, key kelp grazers, in check (Johnson *et al.* 2011). Over the past several decades, two local manifestations of climate change, warming sea surface temperature and a strengthening of the East Australian Current leading to a southwards shift in ocean climatology of around three degrees latitude since 1944 (Hill *et al.* 2008) and range extension of the long-spined sea urchin *Centrostephanus rodgersii* from subtropical Australia. Sea temperatures off Tasmania are now sufficiently warm for regular urchin invasions and for local recruitment of this climate migrant, whose larval development has been experimentally shown to require summer water temperatures > 12 °C (Ling *et al.* 2009). In yet another synergism between different anthropogenic factors, the local increase in urchin abundance off Tasmania is likely assisted by extensive fishing of rock lobsters, since large lobsters are the sole predators on the adult urchins.

Current abundance of long-spined sea urchins off Tasmania has led to loss of biodiversity. Urchins have over-grazed kelp and generated urchin barrens – denuded former kelp forests that support fewer resident species. This case study is a clear example in which simple attribution of kelp declines to locally warming water temperature would be misleading. Climate change and lobster-fishing have influenced a key ecological interaction – grazing on kelp by the long-spined sea urchin – and this in turn has driven kelp declines. This case study highlights how other human stresses can interact synergistically with climate change. Even more importantly, knowledge of the synergistic interaction between a local stressor (here fishing) and climate change is being used for adaptation management of an invasive species. Trials are being conducted in which large lobsters are being restocked, to assess whether this can halt the decline of giant kelp forests, despite continued warming, and continued urchin migration into the region.


Kelp t=143
Low T
T ↗
No fishing
T ↗
Fishing
T ↗
Fish+Reintro
Urchin t=143
Lobster t=143
TAXI
Temperature t=143
1.1
0.96
0.83
0.69
0.55
0.41
0.28
0.14
0
x
y
−0.50
−0.25
0.00
0.25
0.50
0.4
0.2
0.0
−0.2
−0.4

From network to PDE (& vice-versa)

- Use network inference tool python package *graph-tool* *[T. Peixoto]* to
  - *generate (non-dynamic) networks*
  - *Visualise & analyse effective community assembly in postproc*

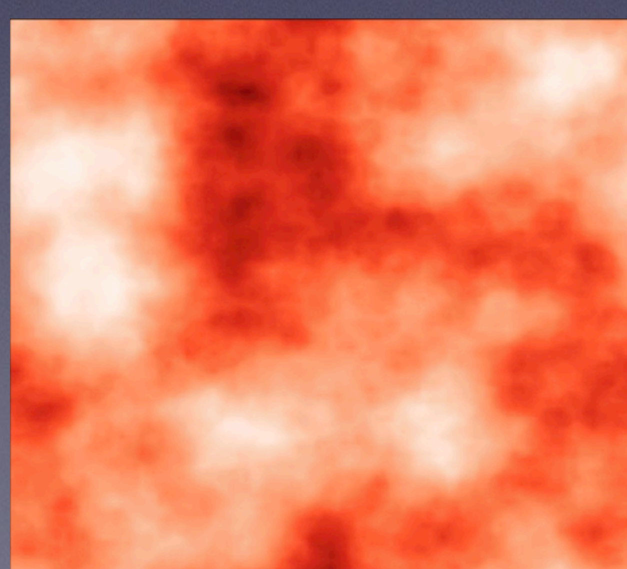



```
void MyAfunc(DataBlock &data, const real t, IdefixArray2D<real> &Aarray) {
  int nSpecies = data.eco->nSpecies;
  real nonNeutral = data.eco->nonNeutralComponent;
  auto species=data.eco->species;
  auto network = data.eco->network;

  if (network=="None") {
    std::stringstream msg;
    msg << "Species interactions have been enrolled but no network is given in input " << network << std::endl;
    IDEFIX_ERROR(msg);
  }

  std::vector<std::string> coords({network+"_speciesindices.npy",network+"_speciesindices.npy"});
  LookupTable<2> csvnpy(coords, std::string(network+".npy"));

  idefix_for("Afunc", 0, nSpecies, 0, nSpecies,
            KOKKOS_LAMBDA(const int s, const int sprime) {
                  real ssprime[2];
              ssprime[0] = s;
              ssprime[1] = sprime;
              Aarray(s,sprime) = nonNeutral*0.4*csvnpy.Get(ssprime);
//              idfx::cout << ssprime[0] << ' ' << ssprime[1] << ' ' << csvnpy.Get(ssprime) << std::endl;
  });
```



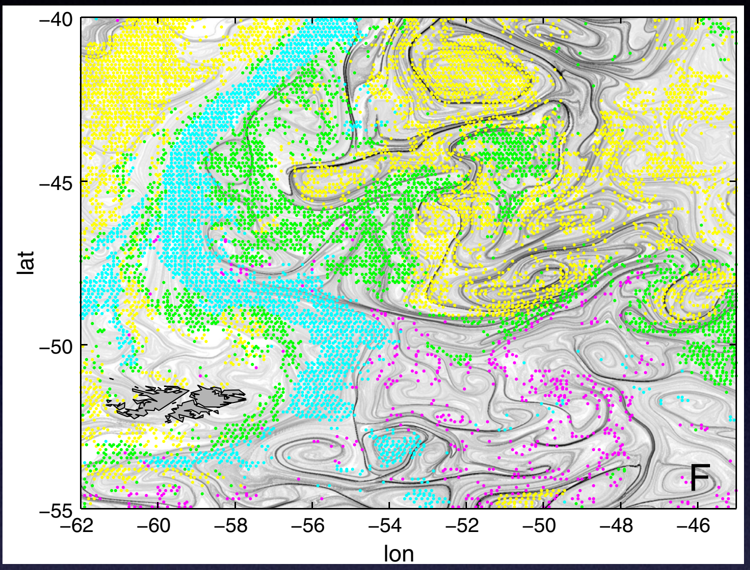
Use idefix's csvnpy function to read network

2D community assembly for random network of 128 species

Fluid mixing effects in marine ecology

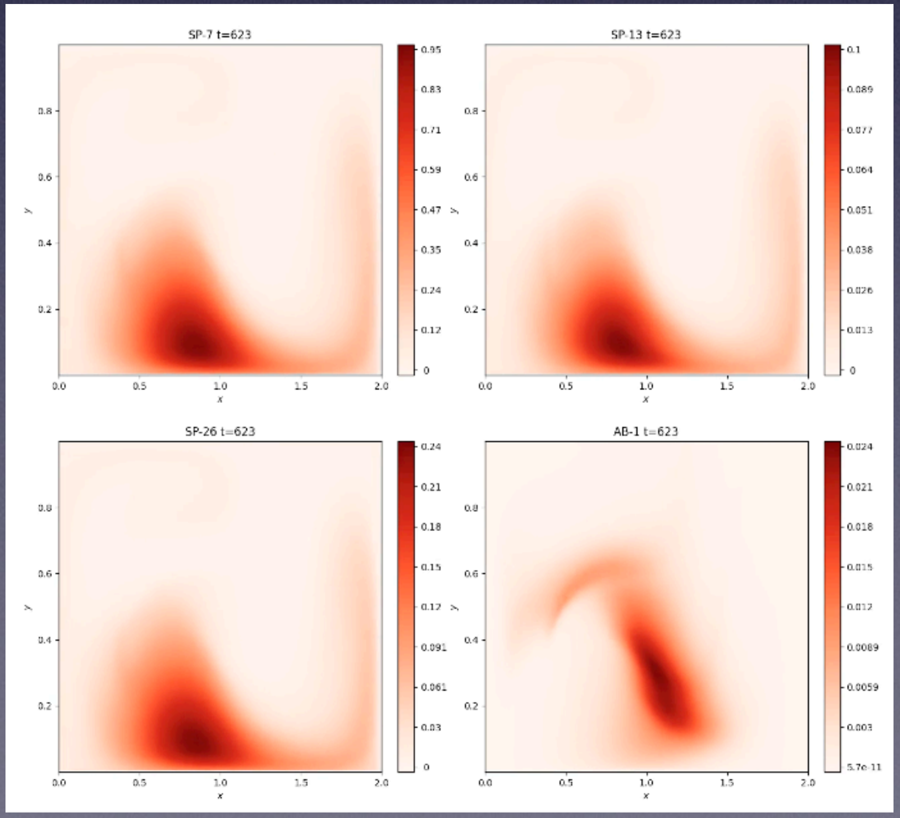
- How is marine biodiversity & function affected by mixing ?
    - Plankton community dynamics
    - Chaotic fluid mixing
    - Indirect competition for nutrients

d'Ovidio et al./UPMC/CNRS



- Effects of currents on (Eulerian) eco measurements
    - Synthetic data can guide sampling and analysis strategies

- Work with J. Montoya, B. Vidella & Alex Genin



Horizon project

BIOcean5D

Nonlinear, multiscale spatio-temporal community dynamics

- Understand spatial scaling laws in ecosystems (Species-Area relationships)
  - Adopt a dynamical perspective rather than empirical species distribution models
- Project has both a modelling and data analysis component
  1. What nonlinear interaction terms and spatial dependences of interactions ?)
  2. Explore and calibrate numerical models to data to make them meaningful
  3. Use model to study impacts of spatial fragmentation and explore possible spatial biodiversity conservation strategies
- ECOSCALES INSU/INEE, MITI 80|Prime funding [w. J. Montoya (SETE)]
  - 1 PhD (starting now) + Server (3x Nvidia A30 GPU + 2x 24 core Xeon)

MITI 80|Prime
Mission pour les Initiatives Transverses et Interdisciplinaires

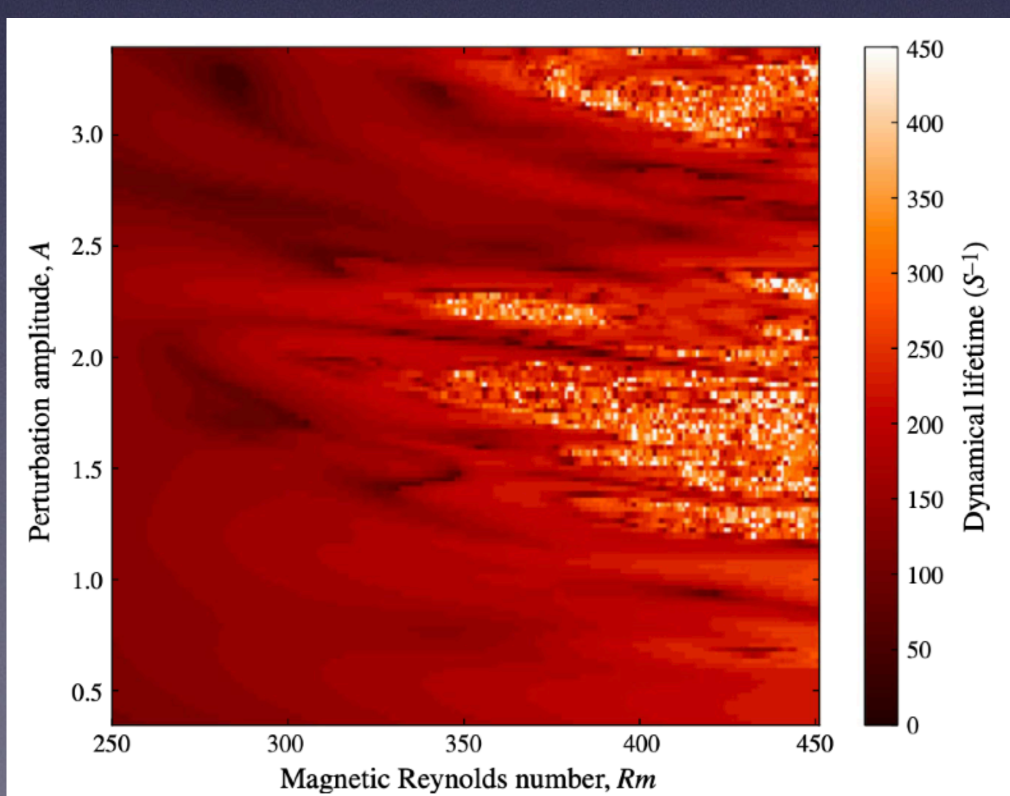
Nonlinear stability: from the MRI dynamo to ecological tipping points ?

Applying for funding / Jeff Arnoldi (SETE)…

J. Fluid Mech. (2013), *vol.* 731, *pp.* 1–45. © Cambridge University Press 2013 1
doi:10.1017/jfm.2013.317

Global bifurcations to subcritical magnetorotational dynamo action in Keplerian shear flow

A. Riols[1,2], F. Rincon[1,2,†], C. Cossu[3], G. Lesur[4], P.-Y. Longaretti[4], G. I. Ogilvie[5] and J. Herault[6]



Scaling up our understanding of tipping points

Sonia Kéfi*[1,4], Camille Saade[1], Eric L. Berlow[2], Juliano S. Cabral[3], and Emanuel A. Fronhofer[1]

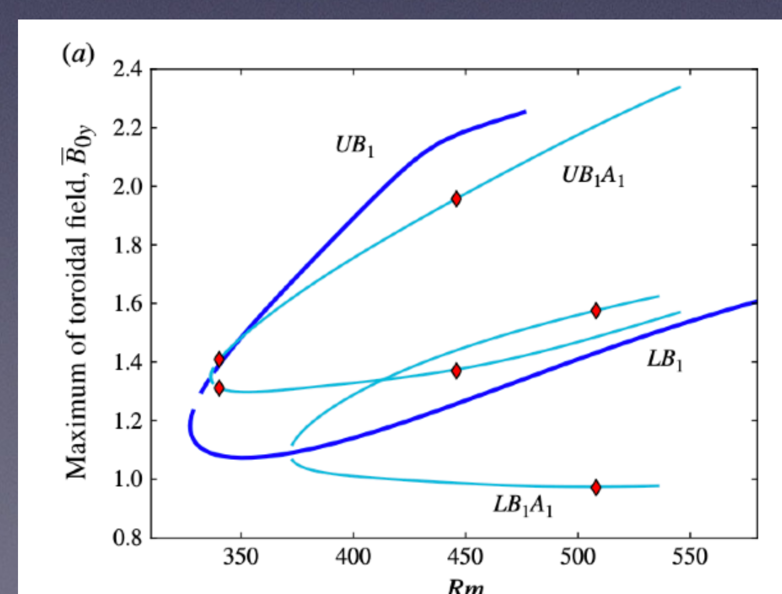
[1]ISEM, CNRS, Univ. Montpellier, IRD, EPHE, Montpellier, France

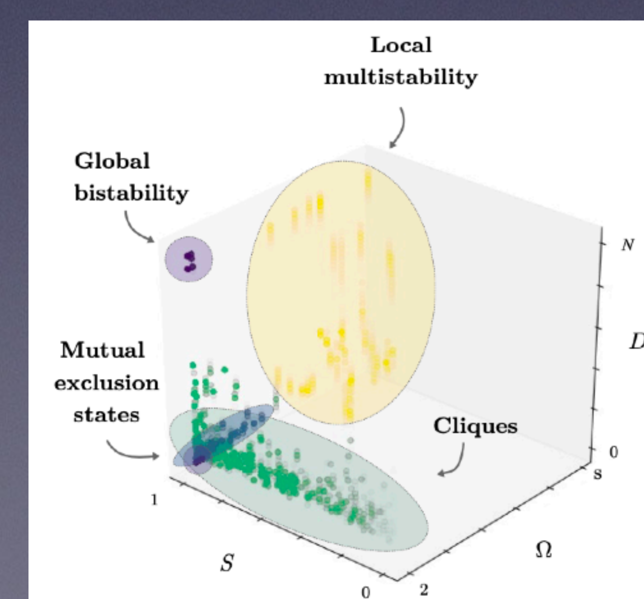
A taxonomy of multiple stable states in complex ecological communities

Guim Aguadé-Gorgorió,[1,*] Jean-François Arnoldi,[2] Matthieu Barbier,[3] and Sonia Kéfi[1,4]
[1] *ISEM, University of Montpellier, CNRS, IRD, EPHE, Montpellier, France*
[2] *Centre for Biodiversity Theory and Modelling, Theoretical and Experimental Ecology Station, CNRS and Paul Sabatier University, 09200 Moulis, France*
[3] *PHIM Plant Health Institute, University of Montpellier, CIRAD, INRAE, Institut Agro, IRD, 34090 Montpellier, France.*
[4] *Santa Fe Institute, 1399 Hyde Park Road, Santa Fe, NM 87501, USA*

(Dated: August 28, 2023)

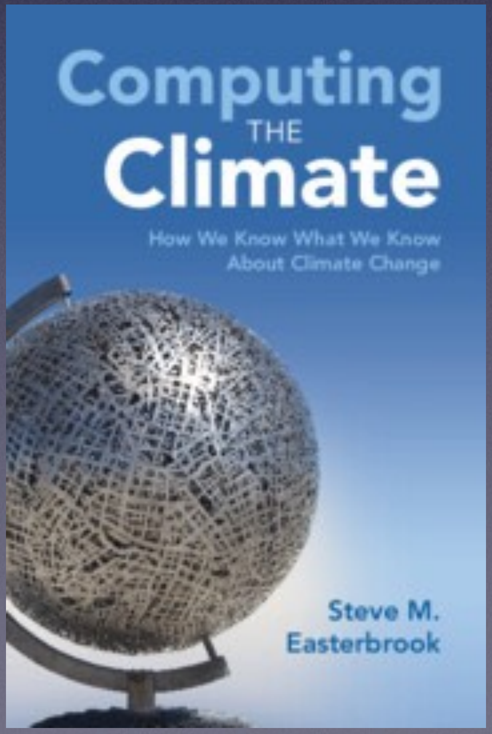
Many natural and man-made systems, from financial markets to ecosystems or the human brain, are built from multiple interconnected units. This complex high-dimensionality hinders our capacity to understand and predict the dynamics, functioning and fragility of these systems. One fragility scenario, particularly relevant to ecological communities of interacting species, concerns so-called regime shifts: abrupt and unexpected transitions from healthy, species-rich communities towards states of degraded ecosystem function and services. The accepted explanation for these shifts is that they arise as abrupt transitions between alternative stable states: multiple stable configura-





Conclusions

- A lot that can be done to improve modelling in ecology
  - "Fluid-like" approach can be useful to model ecological communities
  - But connection to empirical data key to design meaningful models
- Astro codes & methods can help a lot in this kind of fields
  - There's nothing like IDEFIX/ATHENA/PLUTO/RAMSES in ecology
- Is it possible to compute ecosystems ?
  - Take inspiration from climate modelling
  - Codes like IDEFIX can serve as a "dynamical engine"



https://lookingup.francois-rincon.org/