European Research Council

Established by the European Commission

PI: Pascal Tremblin

Understanding atmospheres across the Universe

ATMO

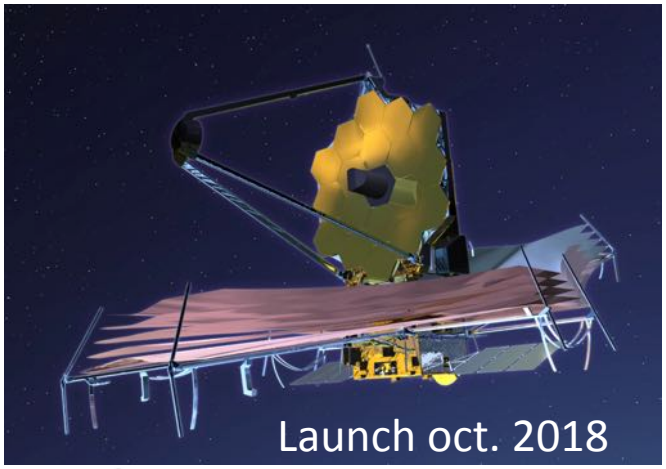
Host Institute: CEA Paris Saclay

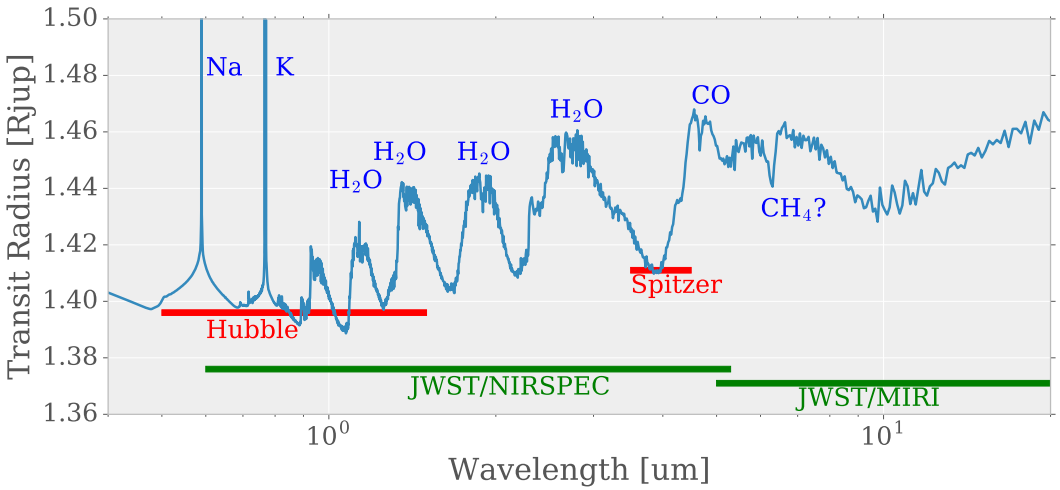
MAISON DE LA SIMULATION

What do we know about exoplanets?

- ≈ 3500 exoplanets discovered with transit or radial velocity technics
  - Get the radius or/and the mass of the planet

- But good-quality data for only a couple of exoplanet atmospheres so far…
  - What are they made of? Which molecules?
  - What is the dynamics of these atmospheres?





Planets & Origins of Life

« JWST will tell us more about the atmospheres of extrasolar planets, and perhaps even find the building blocks of life elsewhere in the universe. »

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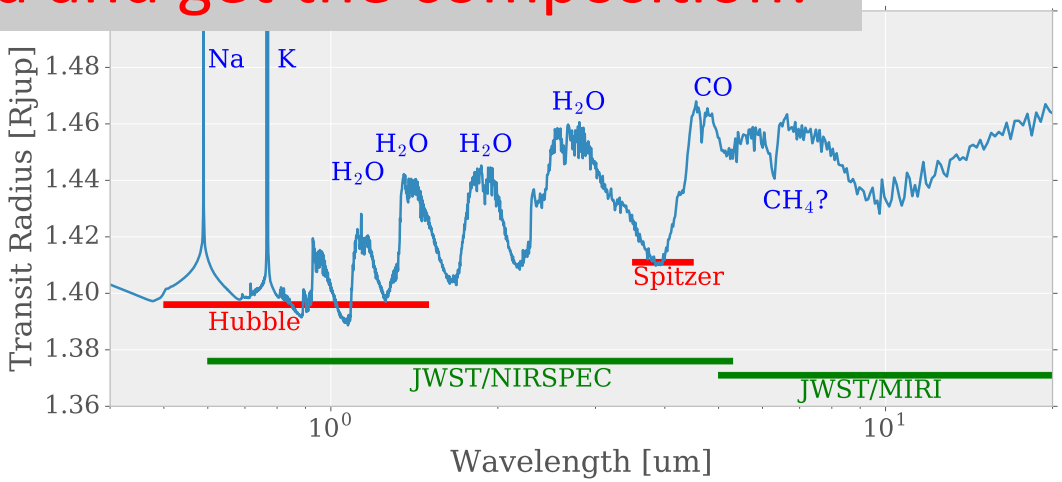
  - W
  - W

Need to have robust atmospheric models to interpret the data and get the composition!



Planets & Origins of Life

« JWST will tell us more about the atmospheres of extrasolar planets, and perhaps even find the building blocks of life elsewhere in the universe. »

Two big questions…

- Non-irradiated exoplanets:

What is shaping their spectra? Clouds or not clouds?

- Irradiated exoplanets:

Why are they inflated? Irradiation from the star or not?

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➢ Non-irradiated exoplanets:

What is shaping their spectra? Clouds or not clouds?

- Still strongly debated…

➢ Irradiated exoplanets:

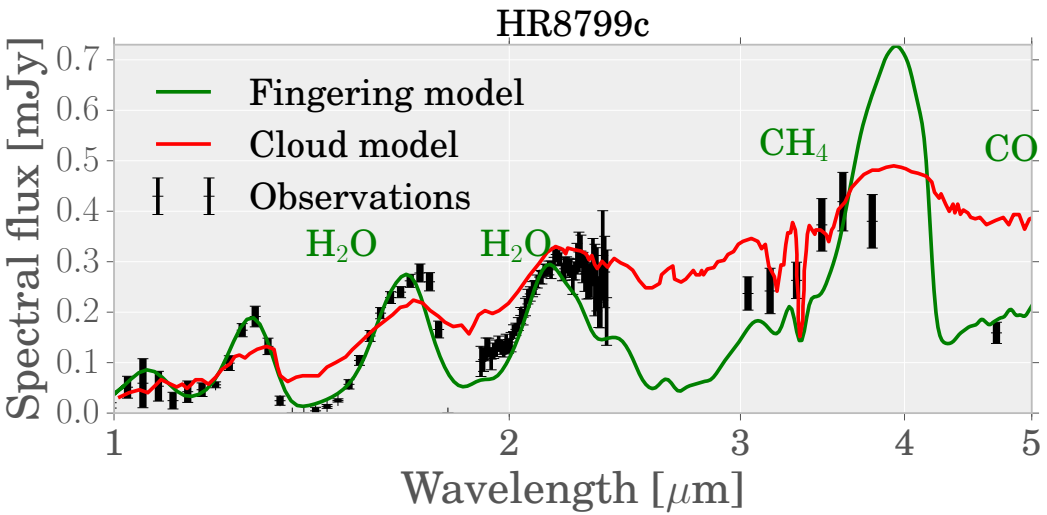
Why are they inflated? Irradiation from the star or not?

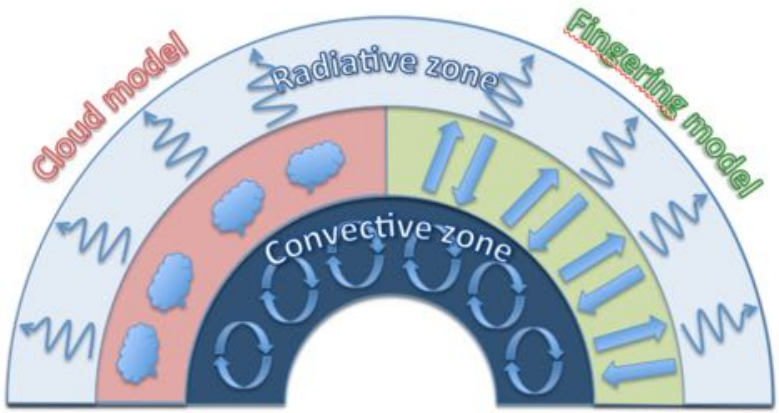
- Still poorly understood…

Major puzzles in astrophysics since the first observations of exoplanets 20 years ago

Paradigm shift 1, non-irradiated exoplanets:
What is shaping their spectra? Clouds or not clouds?

➢ Clouds? Or Fingering convection?





Thermohaline convection
In Earth oceans
(Stern 1960)

Salt-poor water ⇅ Salt-rich water

Fingering convection
in Stars atmosphere
(Théado et al. 2009)

Iron-poor gas ⇅ Iron-rich gas

Fingering convection
in Exoplanets Brown dwarfs
(Tremblin et al. 2015,2016)

CO+3H2 gas ⇅ CH4+H2O gas

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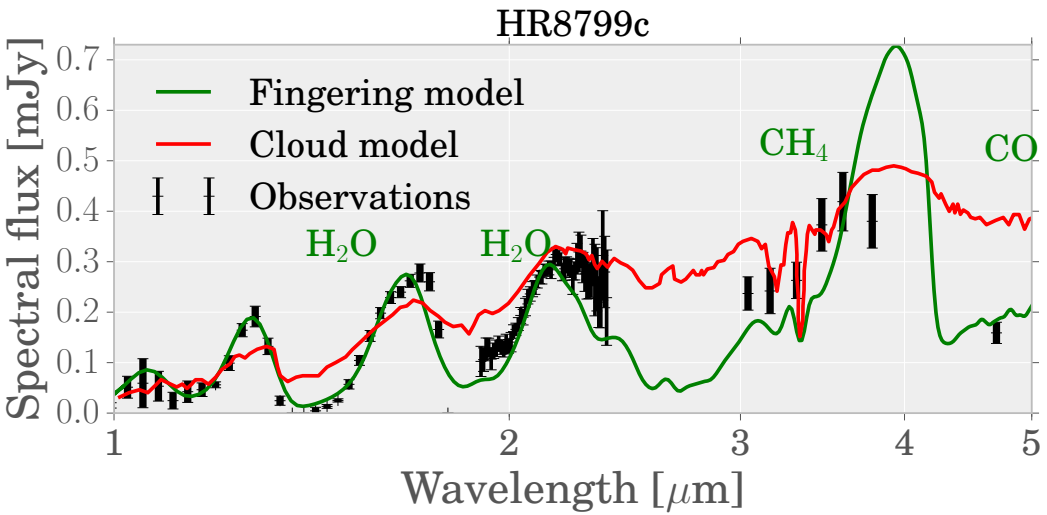
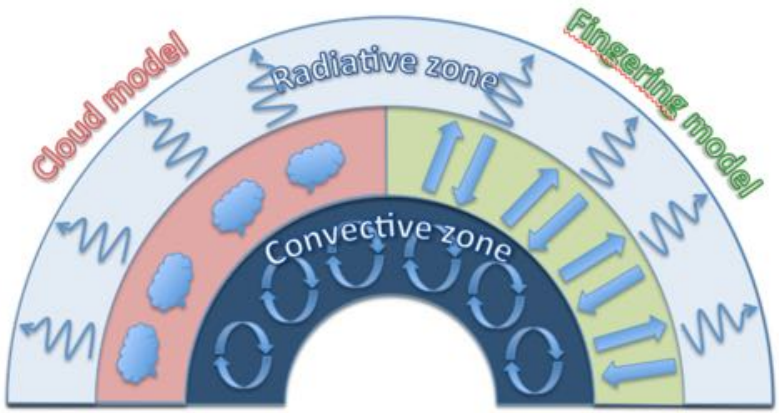




➢ Very promising: a better fit with less parameters! Tremblin et al. (2016)

➢ Paradigm shift: « radical new mechanism to challenge the accepted dogma »

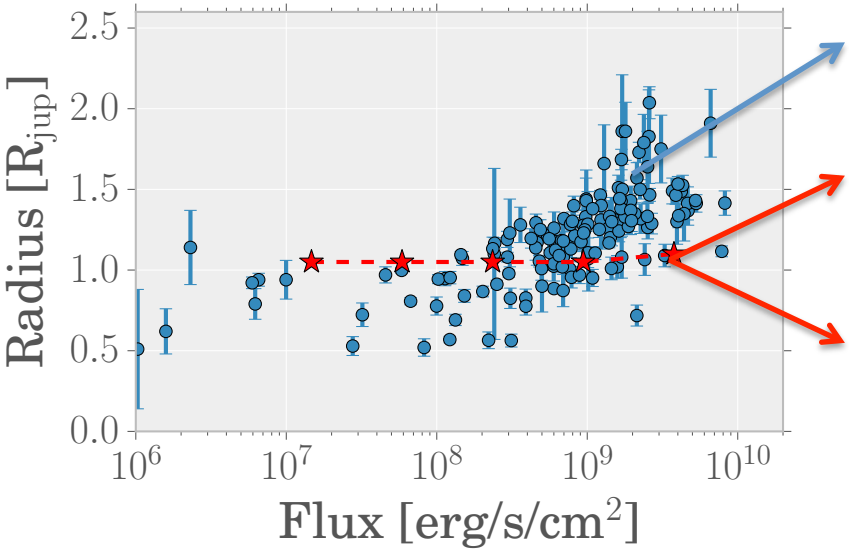
➢ But still a 1D ad-hoc parameterization…

➢ What is the efficiency of realistic 3D fingering convection?

Paradigm shift 2, irradiated exoplanets:
Why are they inflated? Irradiation from the star or not?

- Fingering convection is also expected in irradiated exoplanets… but:

- Charbonneau et al. (1999): Confirmation of the existence of exoplanets with the first transit observation of HD209458b… but irradiated exoplanets are inflated!



- Scale with irradiation
- 1D steady-state model do not work… because of the absence of circulation
- But 3D time-dependent circulation models do not work either… because of the short time-scale circulation?

Still not understood after ≈20 years!

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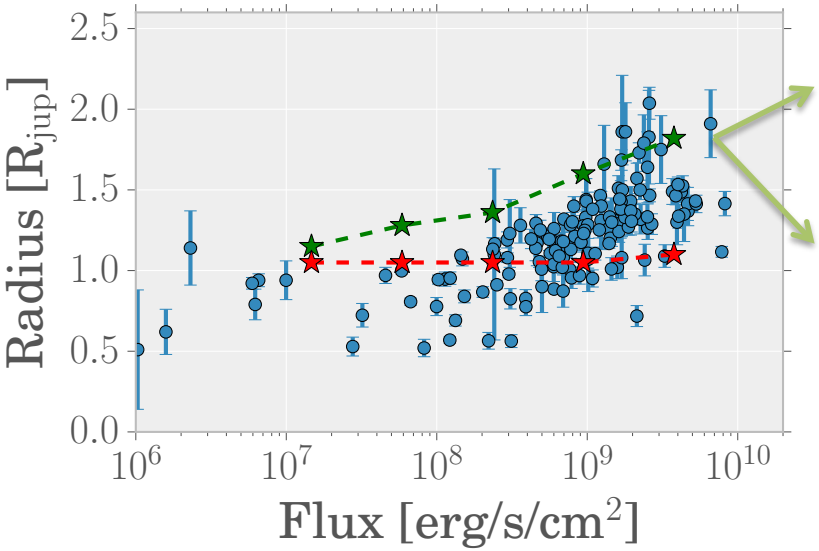


- An innovative approach: A 2D steady-state circulation model works! Tremblin et al. (2017)

- A robust mechanism: The long time-scale circulation leads to heat transport and a large radius

- But what is the 3D long time-scale circulation?
- And what is its impact on fingering convection?

Two big questions…

➢ Non-irradiated exoplanets:

What is shaping their spectra? Clouds or not clouds?

- Still strongly debated…

➢ Irradiated exoplanets:

Why are they inflated? Irradiation from the star or not?

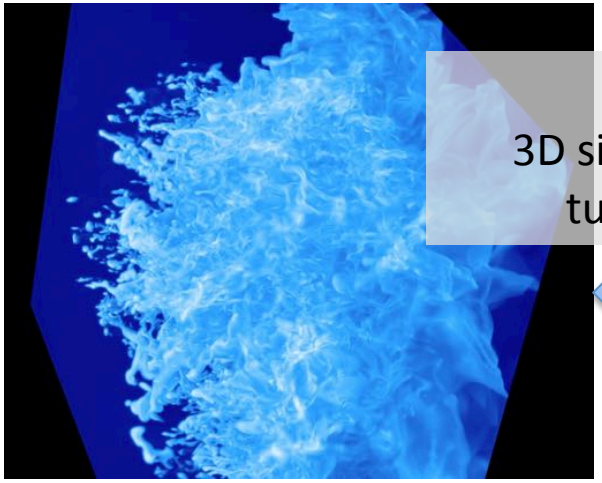
- Still poorly understood…

➢ Need new 3D ab-initio models of fingering convection induced by chemical transitions

➢ Challenge: Space scale are too small

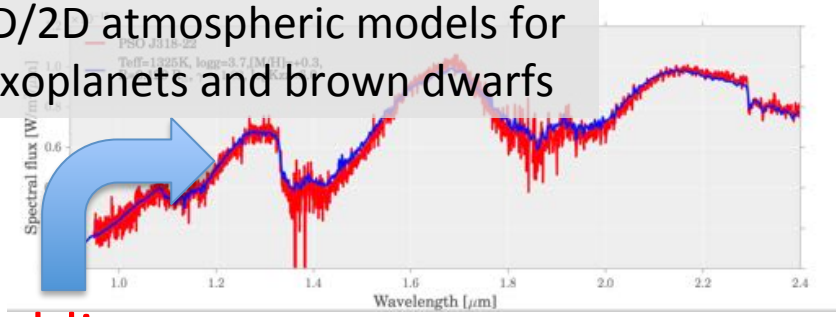
➢ Need new 3D ab-initio models of circulation induced by irradiation

➢ Challenge: Time scale are too long



PhD
3D simulation of turbulence

Postdoc
1D/2D atmospheric models for exoplanets and brown dwarfs



PI: Pascal Tremblin

Understanding atmospheres across the Universe
ATMO

Host Institute: CEA Paris-Saclay

Maison de la Simulation (MDLS)
High Performance Computing (HPC)
Priority access to HPC prototypes

Service d'Astrophysique (SAP)
James Webb Space Telescope (JWST)
Priority access to NIRSPEC/MIRI data

Understanding atmospheres across the Universe
ATMO

- Methodology: Adopt a global approach by studying the atmospheres of stars, brown dwarfs, and non-irradiated/irradiated exoplanets

WP1: Design the numerical tools and study fingering convection in stars

Team: PI, Postdoc1 (2yrs), HPC engineer (5yrs)

WP2: Fingering convection in brown dwarfs and non-irradiated exoplanets

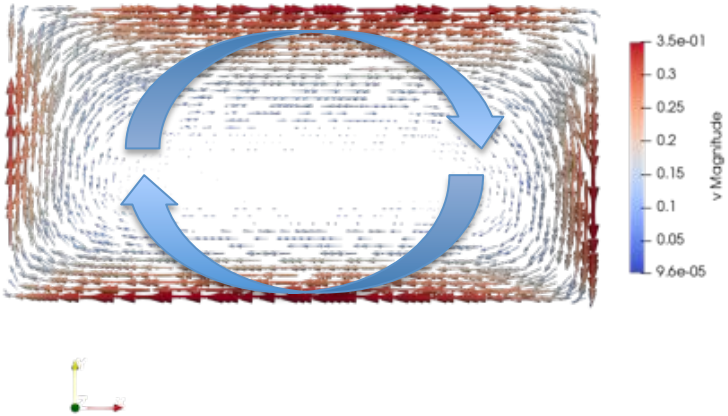
Team: PI, PhD1 (3yrs), HPC engineer (5yrs)

WP3: Fingering convection and circulation in irradiated exoplanets

Team: PI, PhD2 (3yrs), HPC engineer (5yrs)

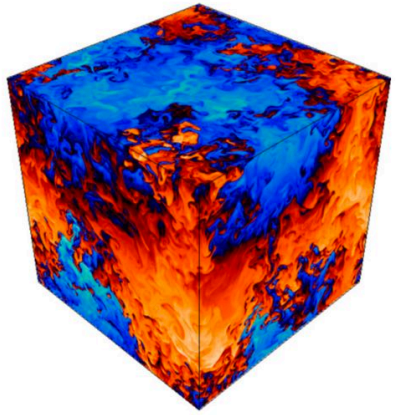
WP1
Fingering convection in stars

Preliminary results of the solver on a high-Mach convection test



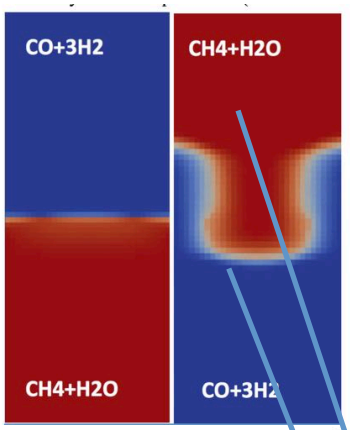
- Design a new robust hydrodynamic solver solving the full Euler equations of hydrodynamics:
  - with stratification (for atmospheres)
  - for low-Mach flows (for fingering convection **WP2**)
  - and high-Mach flows (for fingering convection and circulation **WP3**)

- First application on fingering convection in stars triggered by iron gradients:
  - Comparison with previous works (without stratification, Brown et al. 2013, Garaud et al. 2015)
  - Quantitative estimation of the iron gradients reduction by fingering convection and comparison with observations

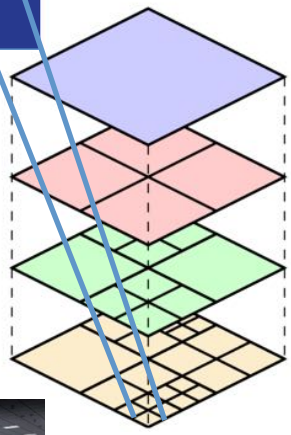


WP2
Fingering convection in Brown dwarfs and exoplanets

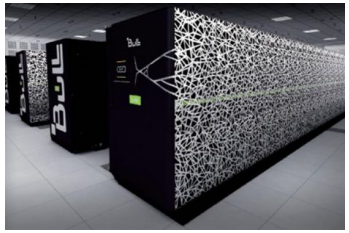
- Develop 3D ab-initio model of fingering convection triggered by chemical transitions (CO/CH4)
- Tackle the small-scale challenge
  - Use Adaptive Mesh Refinement to resolve the small scale fingers and the extension of the atmospheric column
  - Take advantage of PRACE-2 and future new HPC architectures to get the small scales (equivalent of 5000^3 simulation on 1400 next-generation GPUs)



Preliminary results of the fingering CO/CH4 instability



AMR grids



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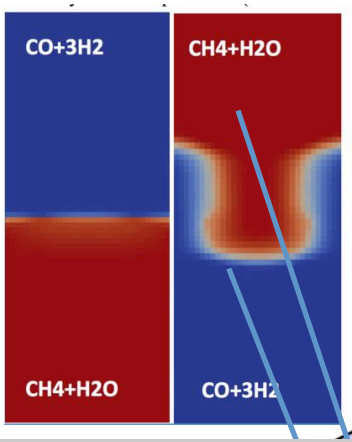

Preliminary results of the fingering CO/CH4 instability

- Develop 3D ab-initio model of fingering convection triggered by chemical transitions (CO/CH4)
- Tackle the small-scale challenge
  - Use Adaptive Mesh Refinement to resolve the
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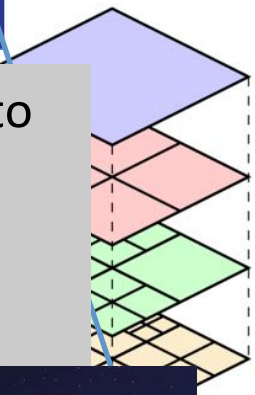
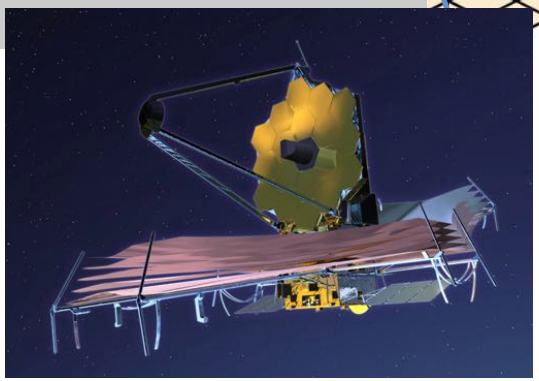


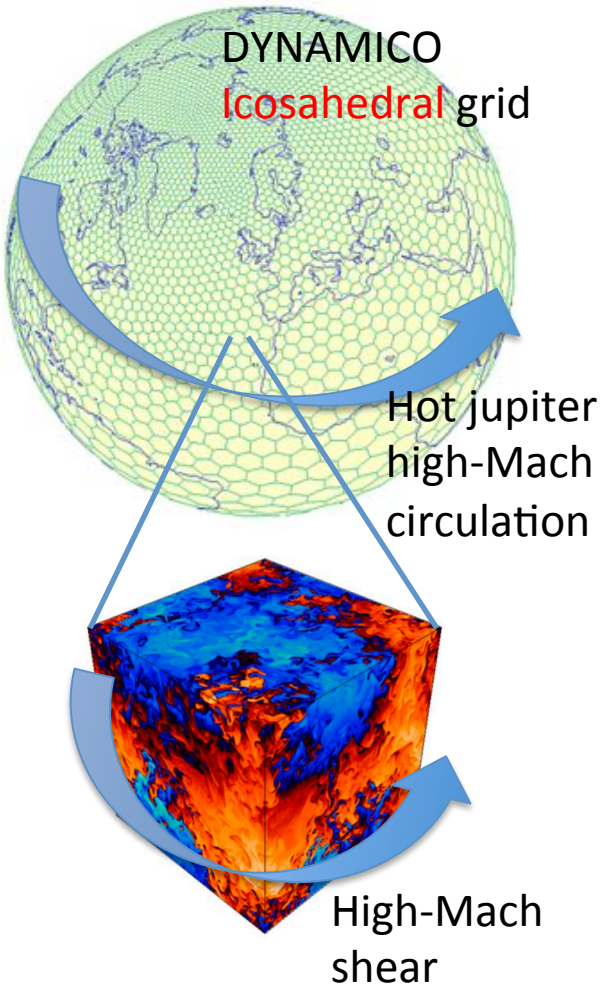
- Provide 3D ab-initio models of CO/CH4 fingering convection to calibrate grids of 1D atmospheric models
- Get the composition of directly-imaged exoplanet observed with JWST



WP3

Fingering convection and circulation in irradiated exoplanets

- Develop a 3D ab-initio model of the long-timescale circulation induced by the irradiation
- Tackle the long timescale challenge
  - By using newly developed Earth circulation model (DYNAMICO) to probe the 3D steady circulation
  - To explain the inflation puzzle
- Characterize the impact of the circulation on fingering convection (destruction or enhancement?)
  - Develop forced shear in 3D local models for fingering convection to take into account the high-Mach circulation



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Fingering convection and circulation in irradiated exoplanets

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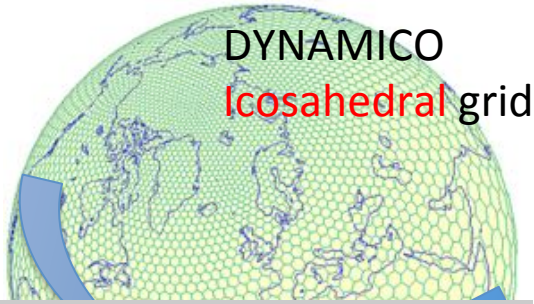

- Provide 3D ab-initio models of CO/CH4 fingering convection with the impact of the circulation to calibrate 1D/2D/3D global atmospheric models

- Get the composition of irradiated exoplanets from transmission/emission spectra observed with JWST

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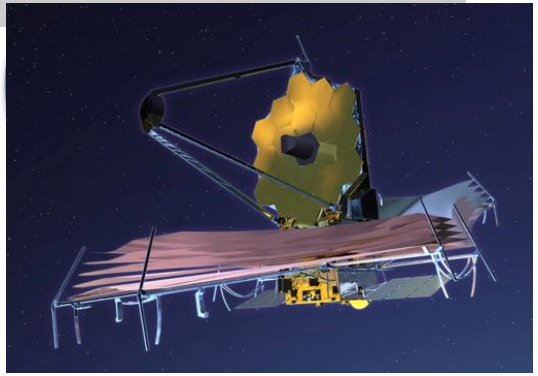
fingering convection to take into account the high-Mach circulation



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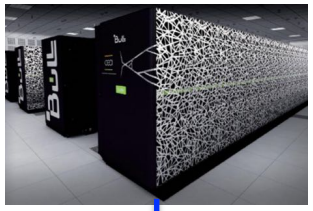
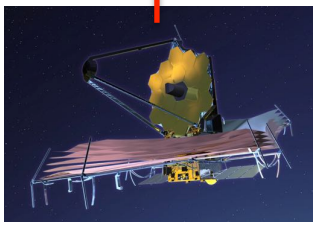
- HPC and observation timescale



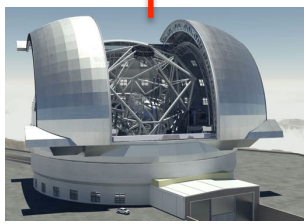
PRACE-2

EXASCALE

2018 — ATMO project — 2023



JWST



E-ELT

WP1: Fingering convection in stars

- Innovative numerical tools
- Applications in stellar atmospheres

WP2: Fingering convection in brown dwarfs and non-irradiated exoplanets

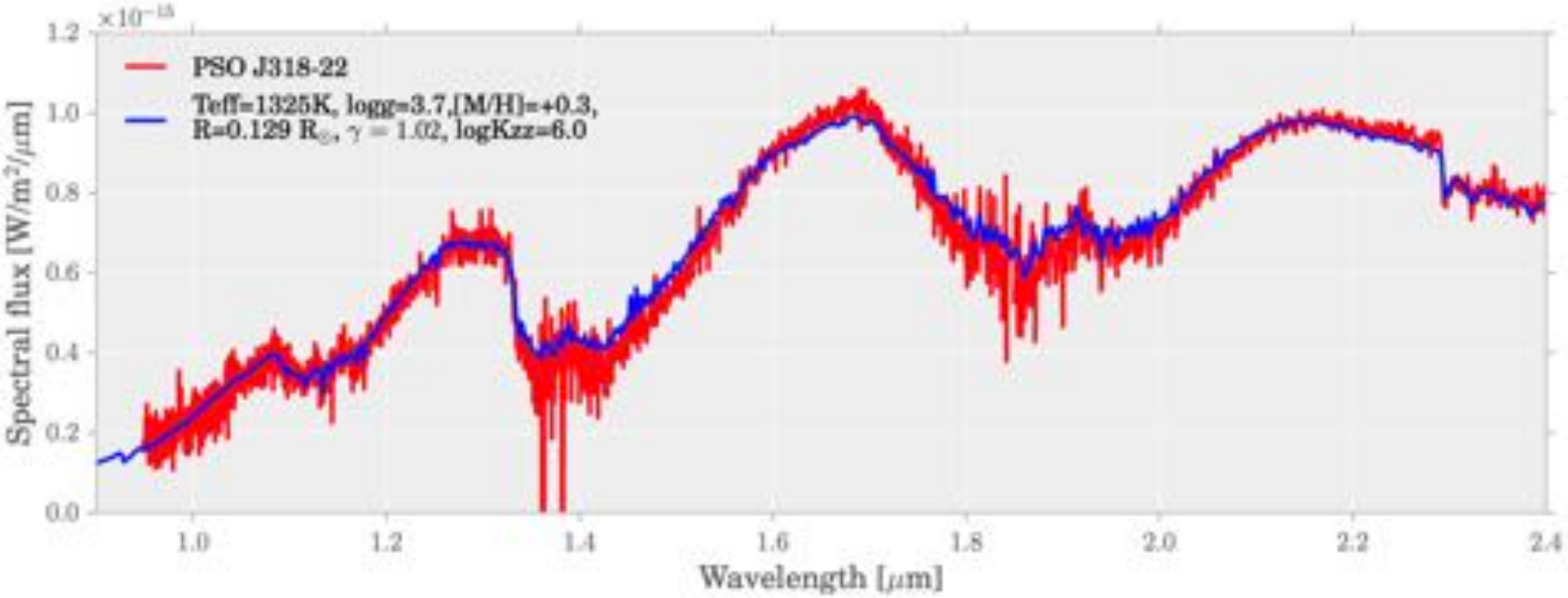
- 3D ab-initio model fingering convection CO/CH4
- 1D atmospheric models for JWST data

WP3: Fingering convection and circulation in irradiated exoplanets

- 3D circulation and impact on fingering convection
- 1D/2D/3D atmospheric models for JWST data

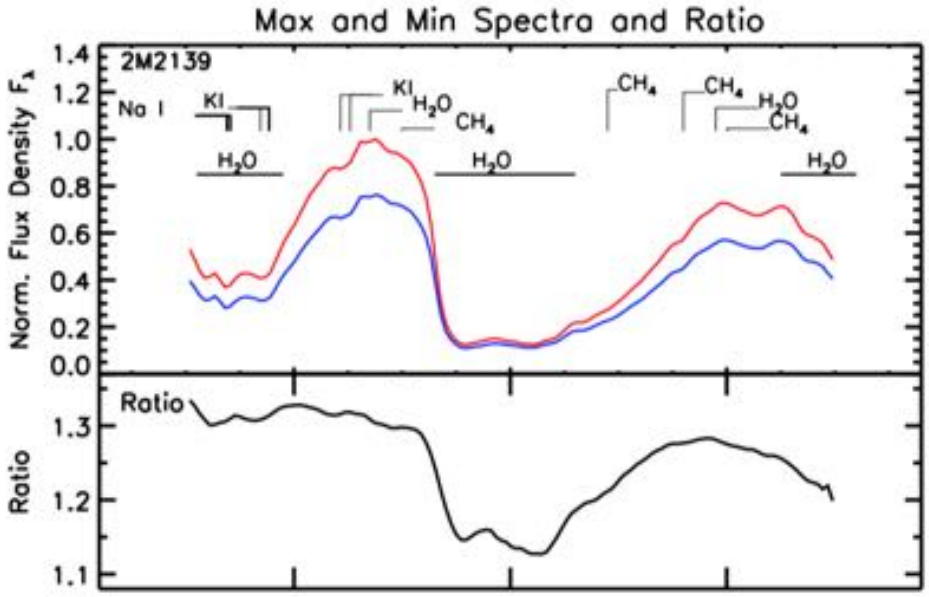
Backup slide

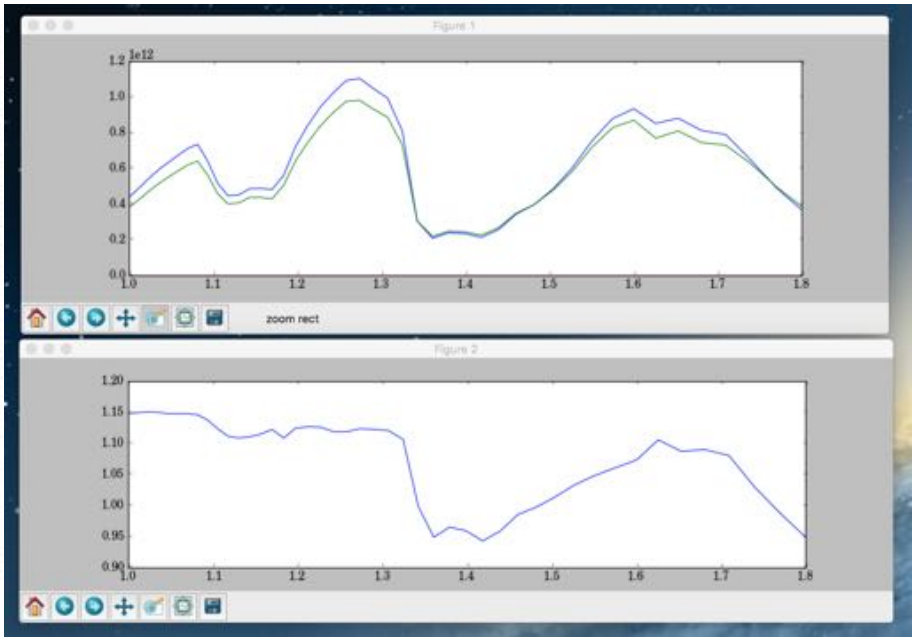
- Low gravity brown dwarfs: cloud models fail but fingering convection works



Backup slide

- Variability: it works too



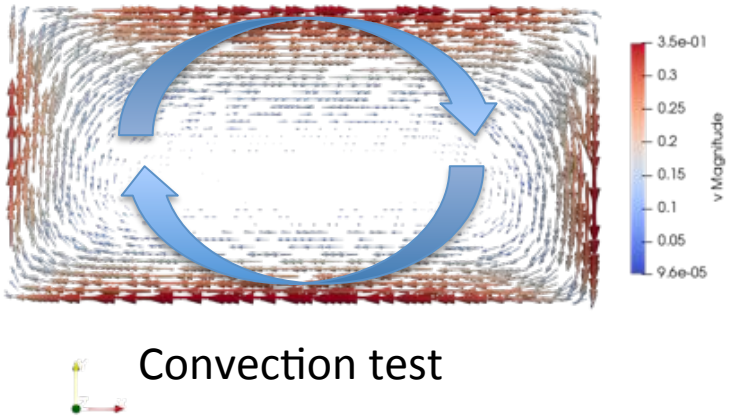


Backup slide

- Design of the « all regime » solver

Preliminary results include:

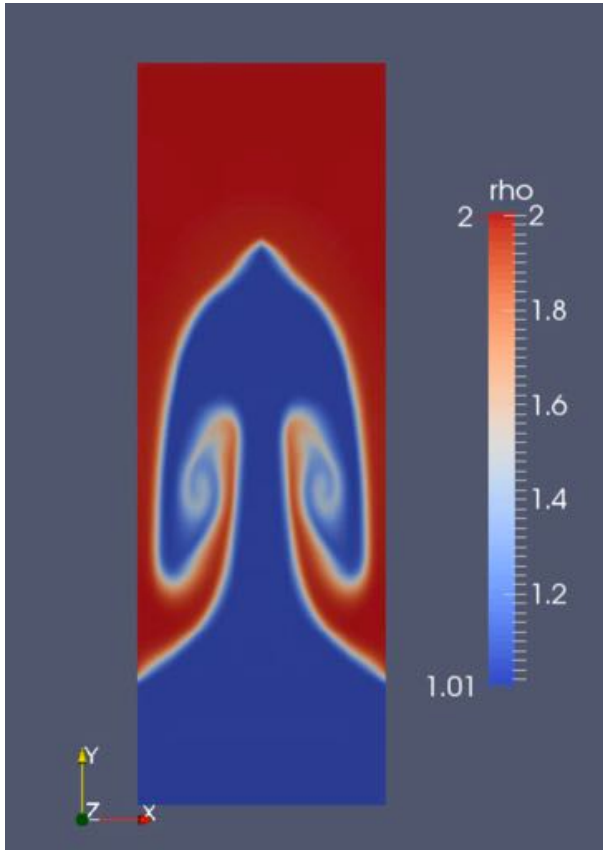
- Well-balanced scheme for gravity
- Low and High-Mach solver for hydrodynamics



Convection test

- Need to go to high order (e. g. MOOD scheme)

Preliminary works on the shallow water equation (Chalons et al. 2016)



Rayleigh Taylor test