Evolution of matter from the interstellar medium to exoplanets with the JWST

Alain Abergel (IAS)

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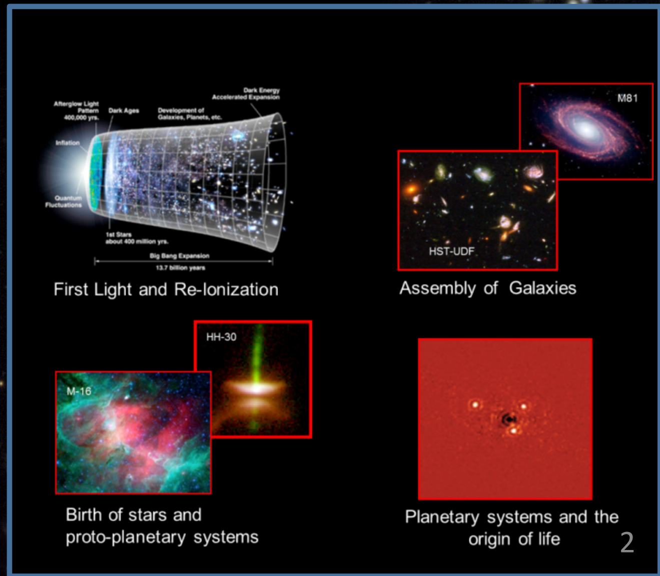
The JWST successor of the HST, :
a 6.5 meter InfraRed telescope in Space

JWST: flagship mission from NASA
with participation of Europe and Canada

Optimized in the IR
To be launched by an Ariane rocket in October 2018
To be in operation for 5 to 10 years (2019→2029)

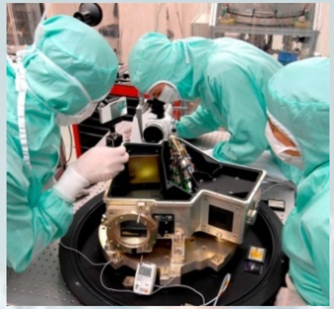
Four IR Instruments:
- NIRIS (0.6-5 μm) (Canada)
- NIRCAM (1-5 μm) (US)
- NIRSPEC (1-5 μm) (ESA)
- MIRI : (5-28 μm) (Europe – US)

Four Scientific Themes:
- First light and the reionisation
- Assembly of galaxies
- Birth of stars and proto-planetary systems
- Planetary systems and the origin of life



French participation : imager of the MIRI instrument

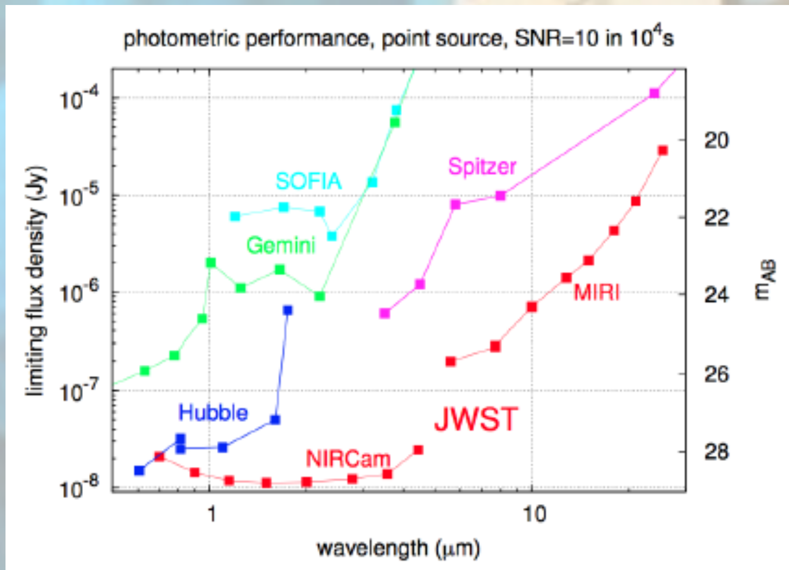
SAp/AIM : technical and scientific responsability,
IAS, Irfu/SIS, Irfu/SEDI (also LAM, LESIA)
Under the final responsibilty of CNES towards ESA

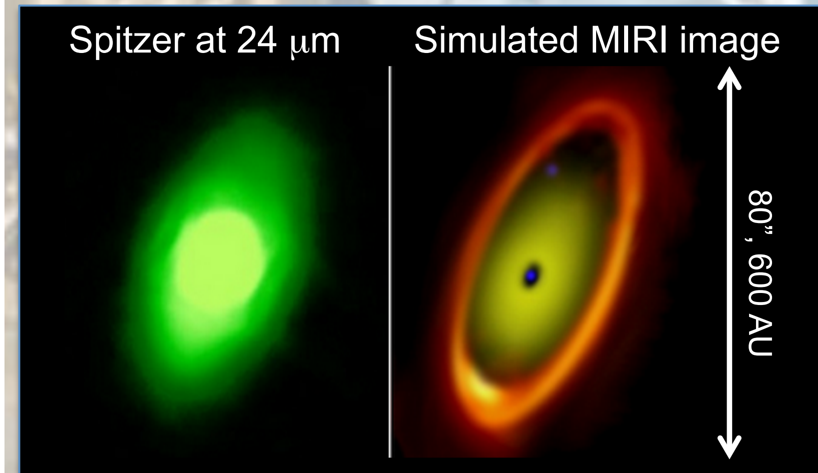


A large gain in

Sensitivity by
1 to 2 orders of magnitude

Angular resolution by
1 order of magnitude





Debris disk around Fomalhaut at 24 μm (Rieke/MIRI team)

Hardware delivered, tests at Saclay, RAL (UK), NASA (Goddard): done
Now working on the **French center of Expertise to be located at Paris-Saclay** (SAp/AIM, IAS, Virtual data)

→ Help the French community to use the MIRI instrument,
→ Developping high level data reduction and analysis tools

JWST Science planning timeline

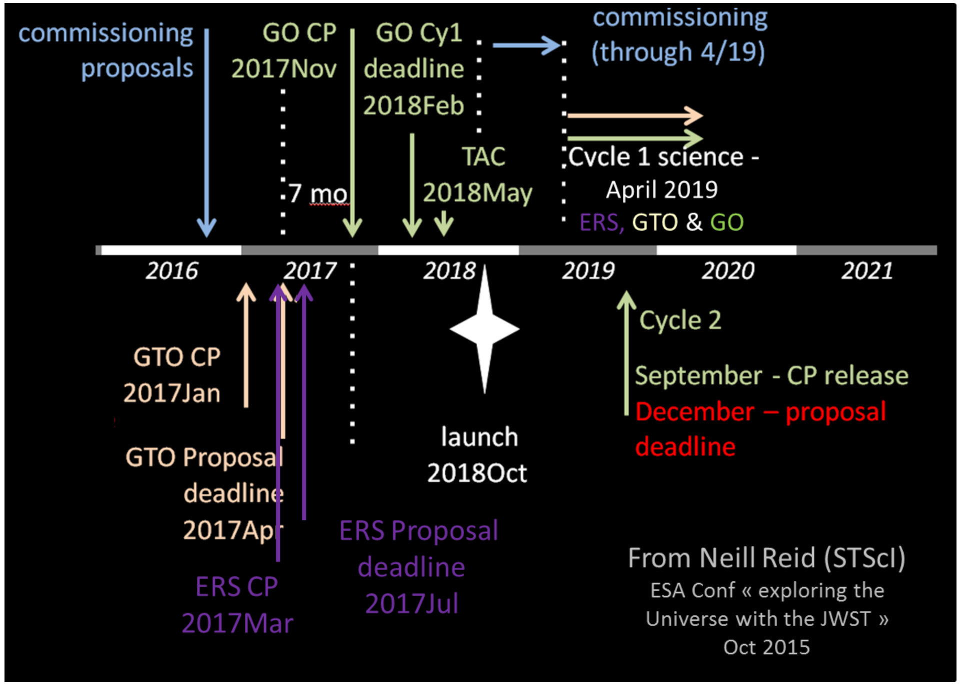
1. Guaranteed Time Observations (GTO) 450 hours for the european MIRI consortium

- Key advantage when building an instrument
- 3 Large Programs : exoplanets, disks, extragalactic (*to be defined by* ***April 2017***)

2. Early Science Release (ERS) 500 hours
call : March 2017; deadline: ***July 2017****.*

3. General Observations (GO): Most of the time attributed following calls :
1st : April 2017; deadline: ***Feb. 2018****.*
2nd: Sept. 2019; deadline: ***Dec. 2019***

On sky comisionning in 2019, then
ERS, GTO and GO observations will start in April 2019.



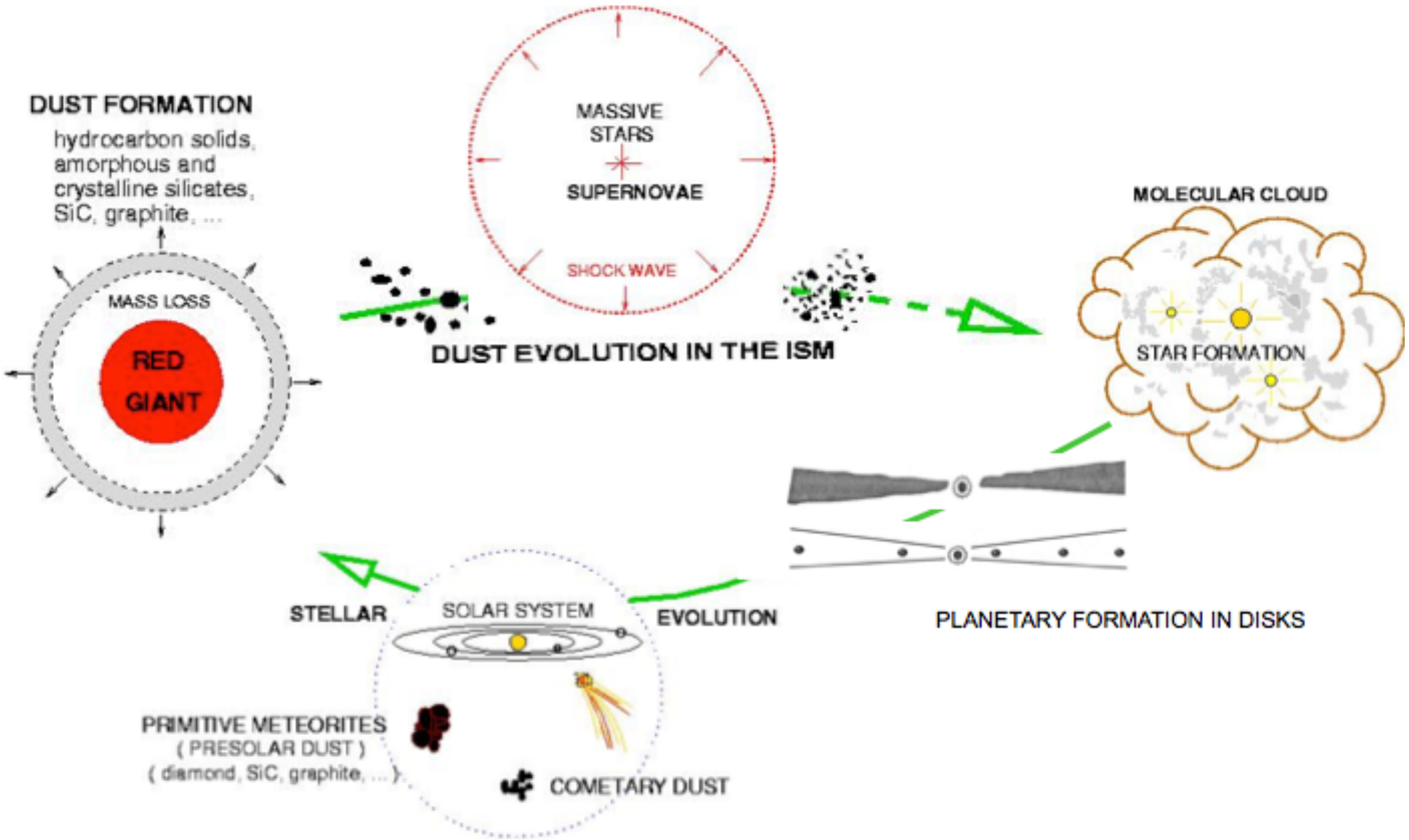
ERS : Data available to all immediately (in order to prepare Cycle 2 GO proposals)
GTO & GO: 1 year proprietary period

The access to the observations and the data analysis will be highly competitive

→ The mid 2016 – end 2019 period is crucial

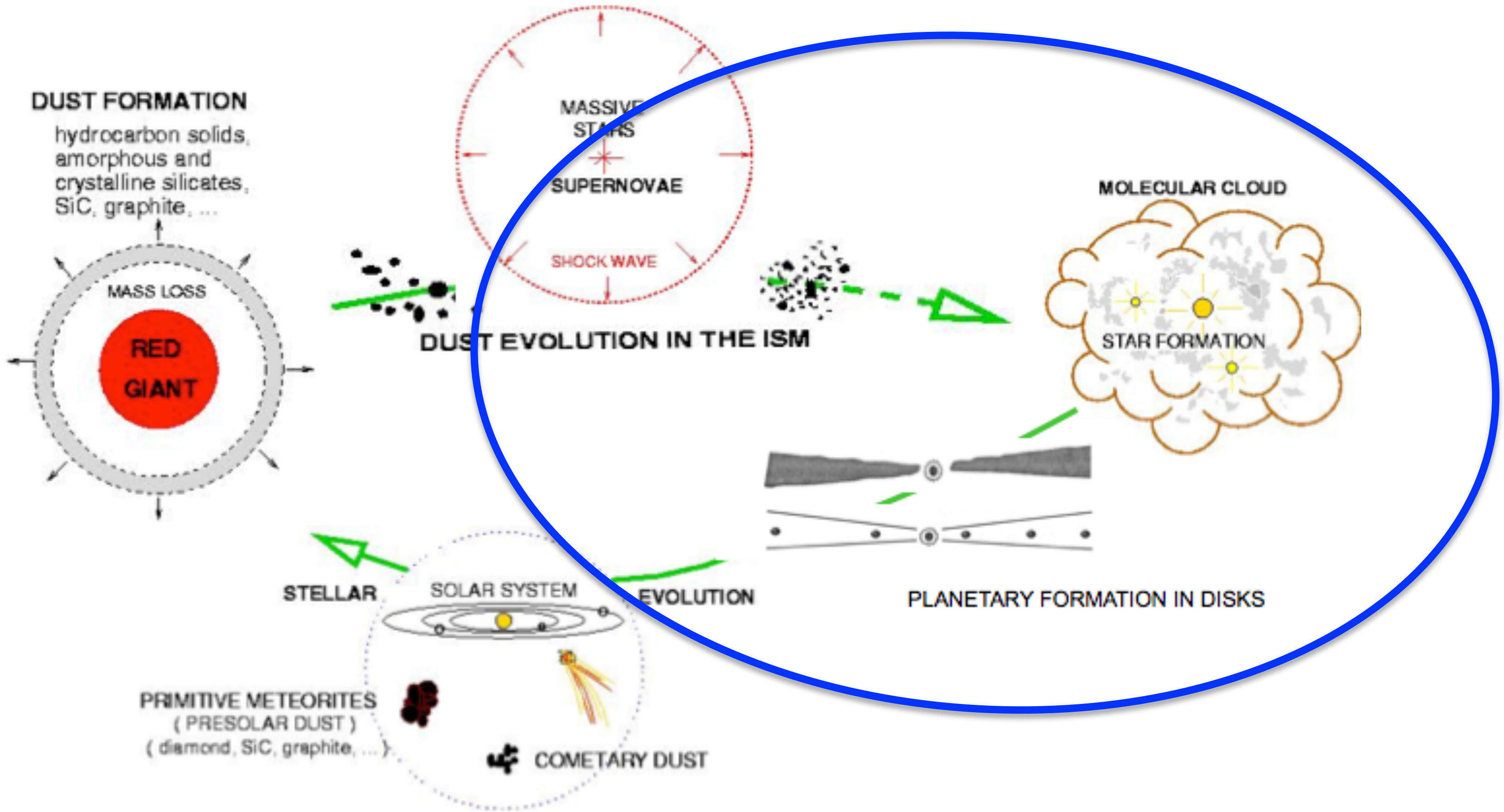
Goals of our project

- Cycle of dust particles in Galaxies :



Goals of our project

- Understanding physical processes which are acting on the matter in the evolutionary sequence from the interstellar medium to the formation of planets



Goals of our project

- Understanding physical processes which are acting on the matter in the evolutionary sequence from the interstellar medium to the formation of planets

- Put together the expertises in several P2IO laboratories (CSNSM, IAS, IPNO, SAp/AIM) in order :

  → to prepare JWST observational programs for interstellar clouds, protoplanetary disks and exoplanets (to be submitted in 2017, 2018, 2019)

  → to analyse the first JWST data (from 2019)

    → Modelling & Simulation tools

    → Laboratory experiments on extraterrestrial samples and analogues

  → to continue the scientific exploitation of the JWST during the next decade

Organisation: 4 work-packages

WP1 Scientific coordination: Alain Abergel (IAS)

- Strenghtening the interactions
- Encouraging interface studies

  modeling/experiments, disks/interstellar medium, exoplanets/disks, …
- Coordination with the french community for the scientific preparation of the JWST (collaborations: CNES, Programmes Nationaux du CNRS, Laboratories)

WP2 Preparation of JWST observations: P.-O. Lagage (SAp/AIM)

WP3 Modeling and simulations : E. Habart (IAS)

WP4 Laboratory experiments : C. Engrand (CNSNM) & A. Aléon-Toppani (IAS)

WP2 : Preparation of the JWST observations

1. Prior to launch (2016-2018)

Task 1: Simulations of JWST observations,
Improving the MIRI simulator to extended sources (disk case)

Tasks 2 & 3: Keep on acquiring expertise (Optics, Detector, etc)
Data reduction pipeline: Implementation, use, improvement
Participation in the data challenges (planned for exoplanets)

2. After launch (2019 - …)

As soon as data are available (great advantage : access to the commissionning data)
run the data reduction pipeline, assess the uncertainties

→ to be rapidly in a position to interpret the data

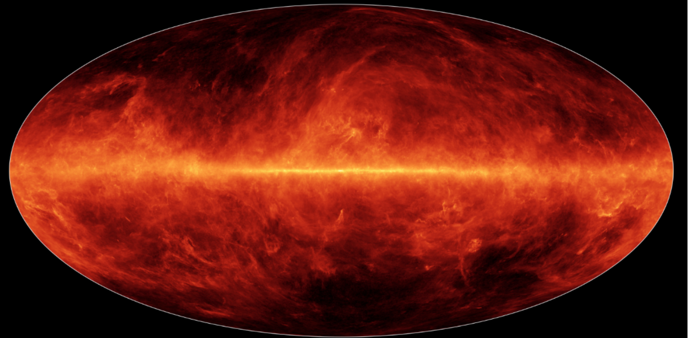
French Center of Expertise for MIRI located at Paris-Saclay (support from CNES)

→ 1 PhD (exoplanet atmosphere characterization with the JWST)

Interstellar dust

Visible (ESO/S. Brunier)

Everywhere
UV-visible → IR-submm



Planck HFI (thermal dust)

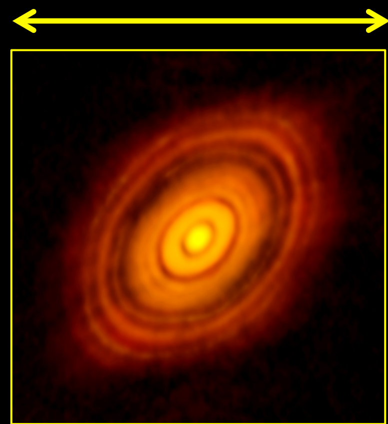
Key actor of matter evolution (gas heating, formation/protection of molecules, etc) at all angular scales :

Herschel, submm, M31

NRAO, visible in Orion

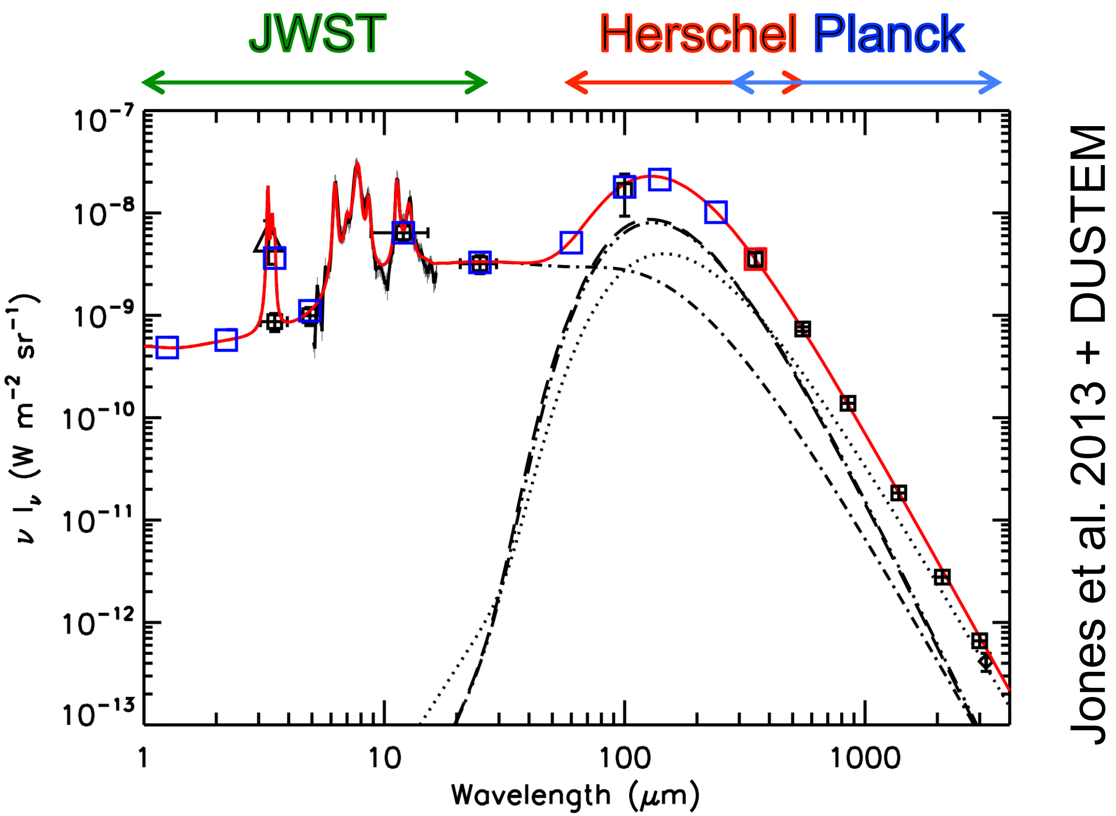
HST visible, M16

2” , 280 AU



ALMA 1 mm, HL Tau

Dust Emission spectrum (diffuse ISM)



- **''Big Grains'' (but size < 1 μm)**: Thermal equilibrium → Herschel & Planck
- **''Very small dust particles'' (nanometric size)**: Stochastically heated → JWST

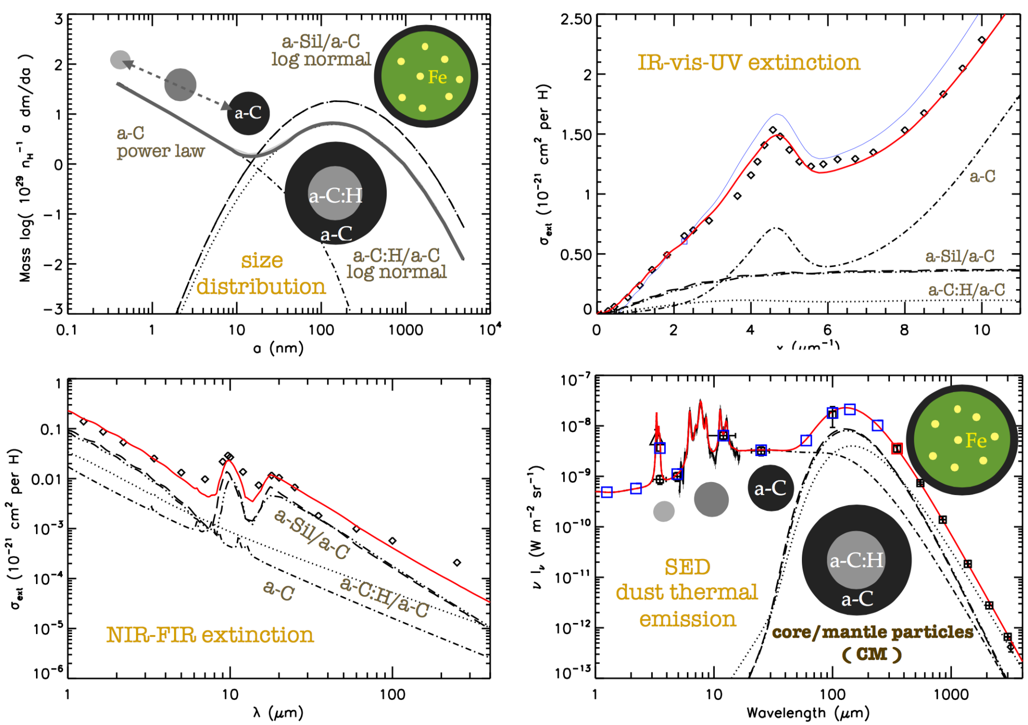
Most that half the total grain surface

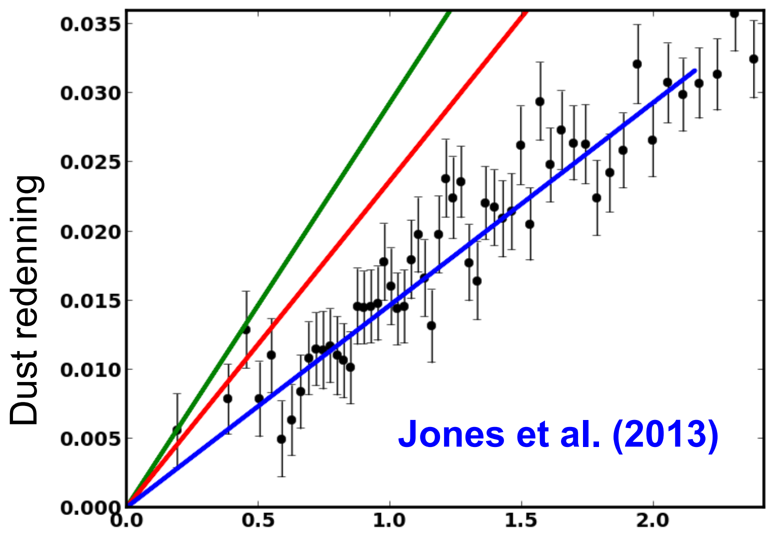
→ Strongly coupled to the gas (Dynamics, Heating, Molecular formation)

→ Major role in the matter evolution

Nature of interstellar dust : reference model @ IAS

Hydrocarbons (a-C:H), amorphous carbon (a-C) and amorphous silicate (a-Sil) grains :





Submm optical depth from Planck XI (2014)

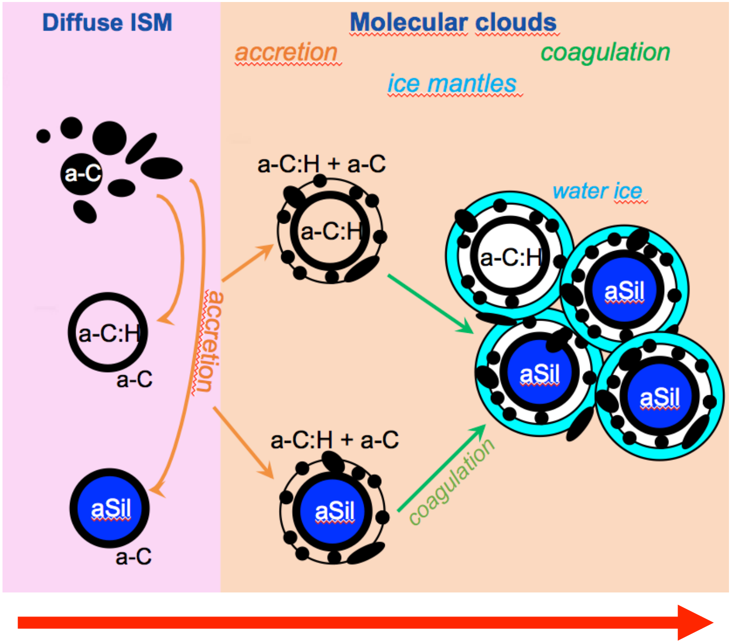
Reference model to analyse the emission and extinction of the dust in the diffuse interstellar matter (Jones et al. 2013)

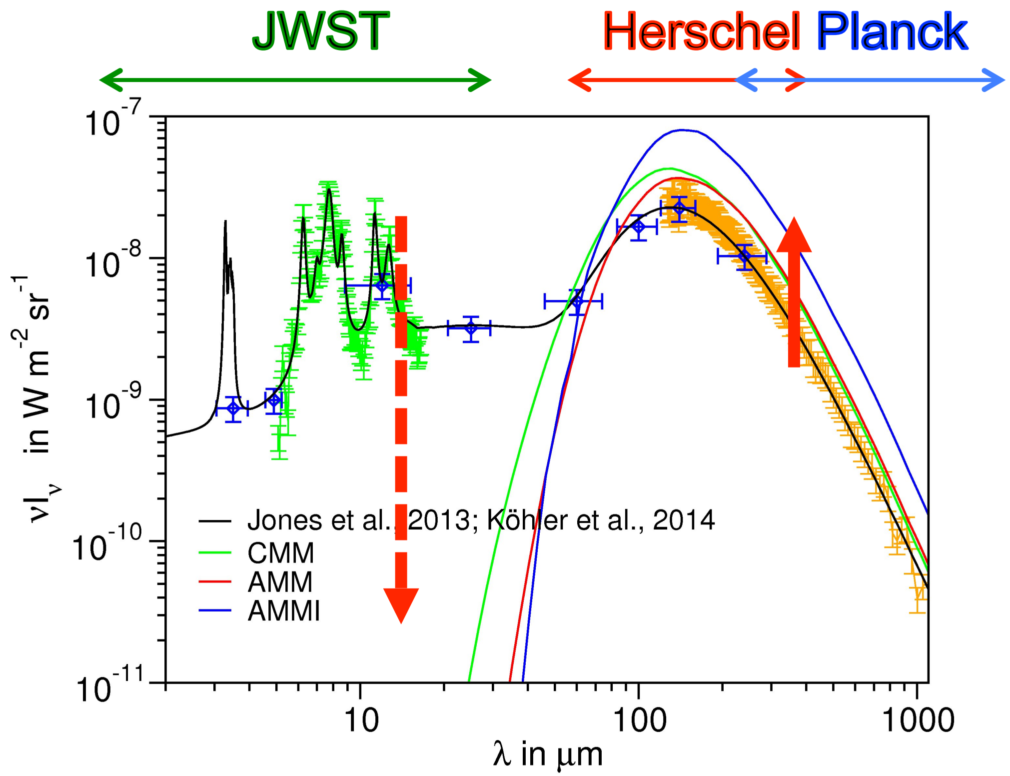
→ Use experimental data that are available

→ Constrained with Planck-Herschel data

Nature of interstellar dust : Evolutionary model

Include evolution with the local density :



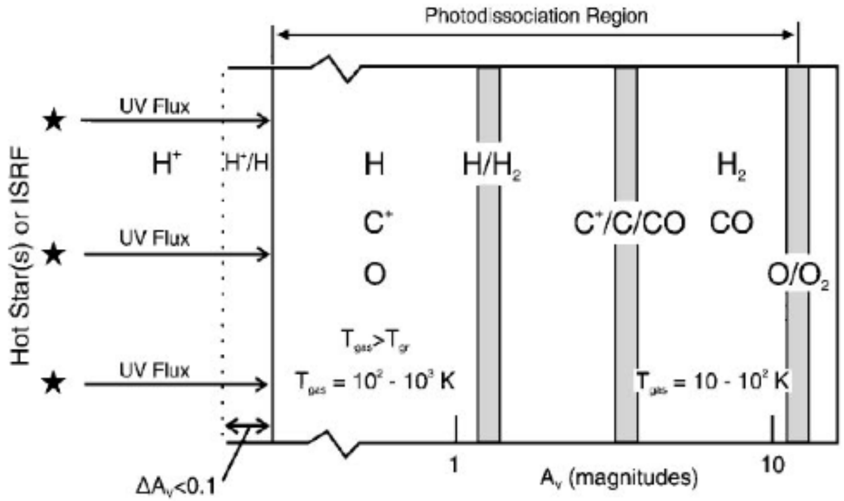


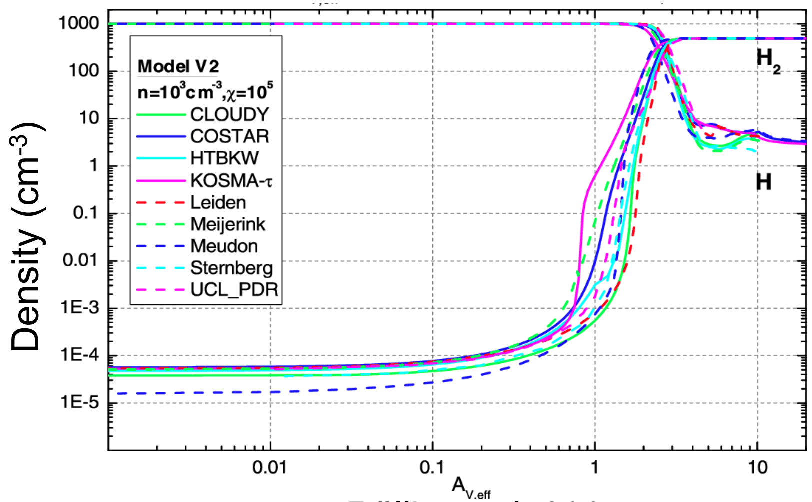
Köhler et al. 2015, Jones et al. 2016

- To be tested on the full emission spectrum and in regions where the density changes, at the interfaces between diffuse & dense regions

Photo-dominated regions (PDRs)

→ **Illuminated Interfaces between diffuse and dense regions**
→ **Ideal to study the evolution of the matter with the density**



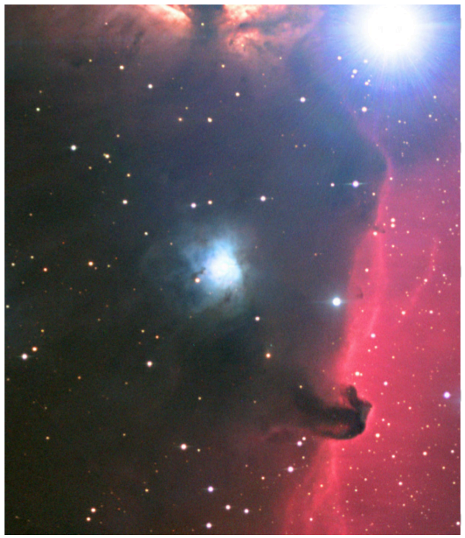


Röllig et al. 2007

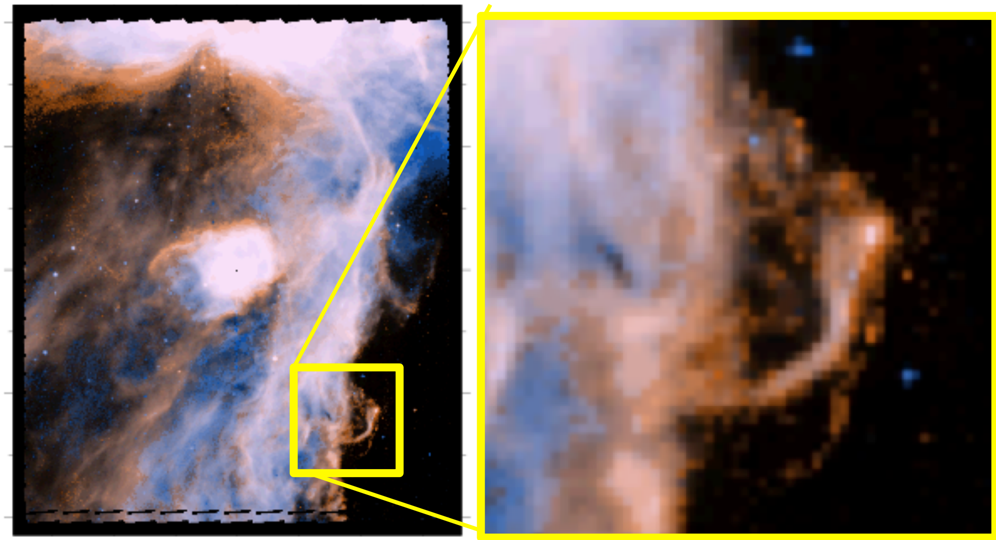
Dust evolution in photo-dominated regions (PDRs)

Visible

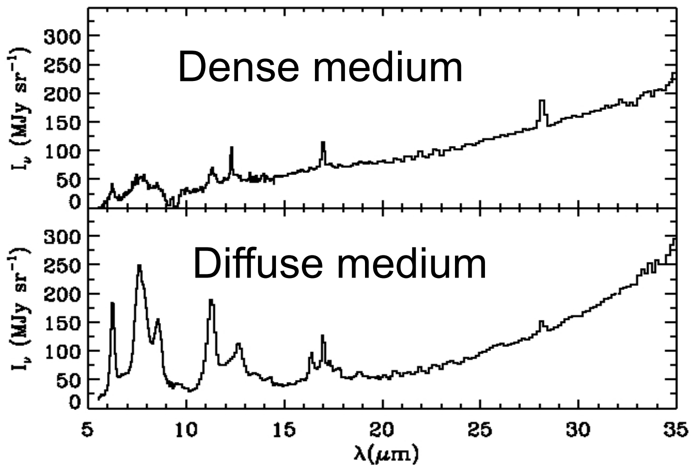
IR emission: Aromatic 5-8 μm
Continuum at 15 μm



NRAO



ISO (Abergel et al. 2002, telescope diameter: 60 cm)



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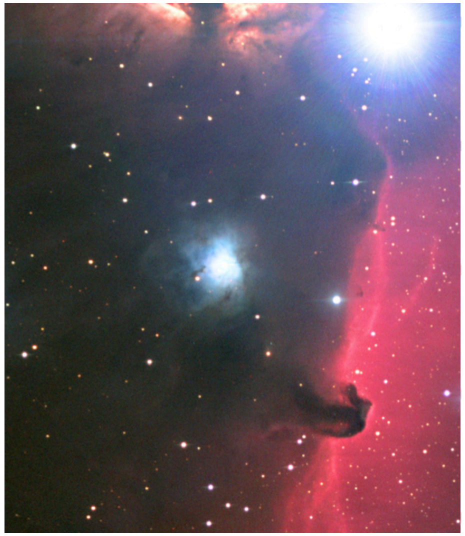

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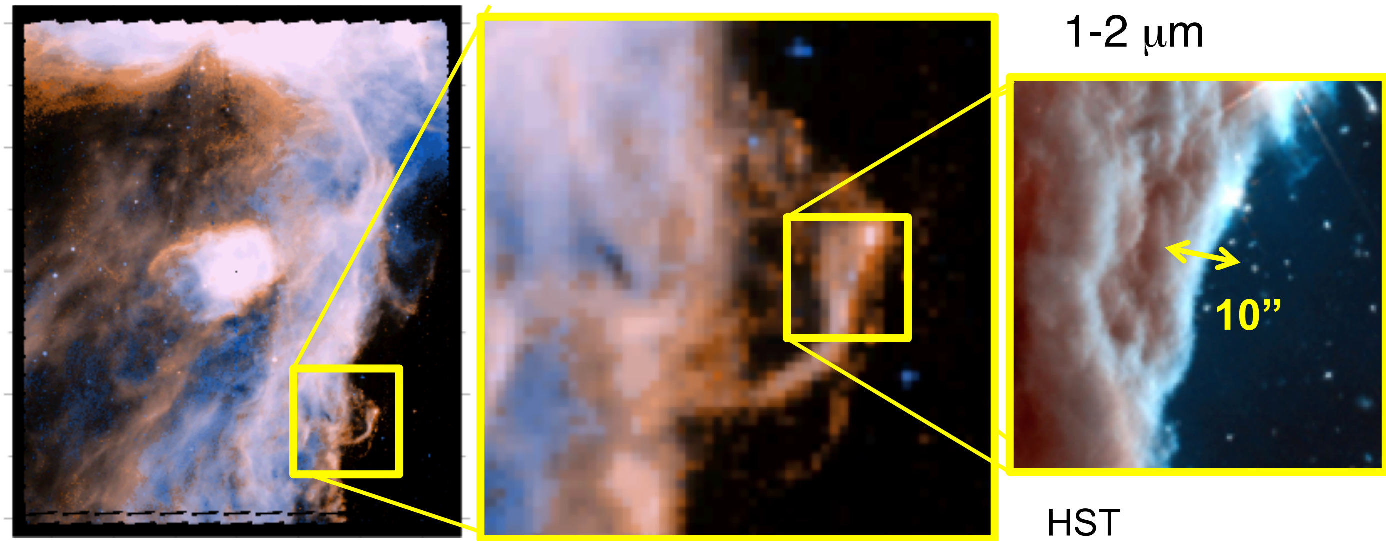
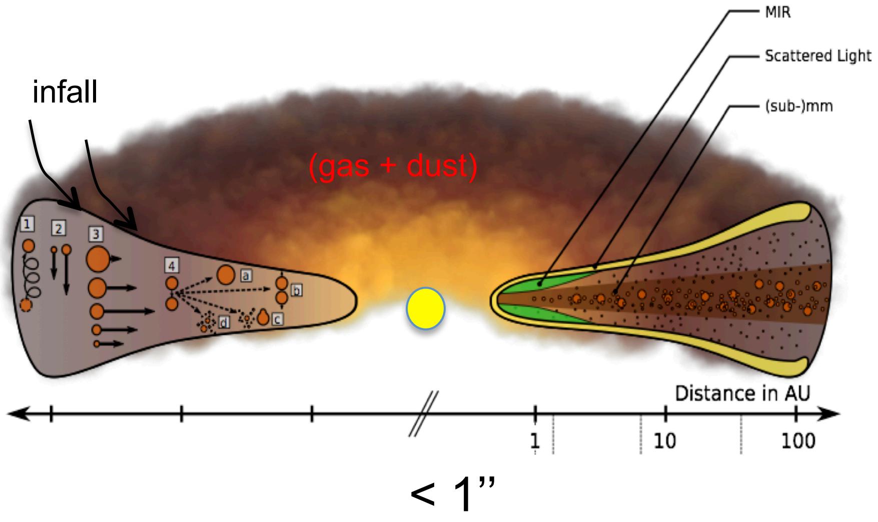


ISO (Abergel et al. 2002, telescope diameter: 60 cm)

JWST : How dust properties change at the interfaces ?

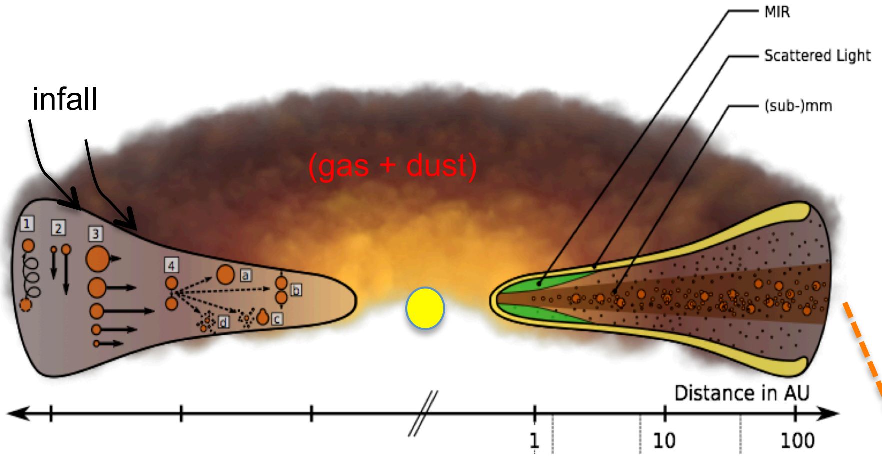
- The JWST has the angular resolution (0.1”-1”) to resolve the interfaces in the IR
- Dust evolution : growing, accretion, fragmentation, charge state, …

Dust evolution in protoplanetary disks

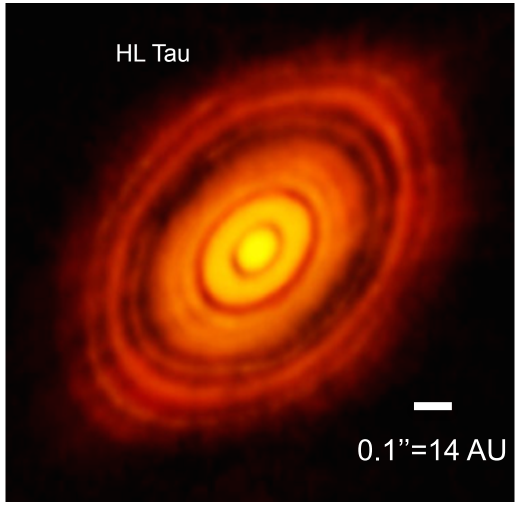


- By-product of the gravitational collapse to form young stars
- Solid matter : Submicronic size → cm size → Planets
- Flared shape :
    - Stellar radiation and stellar winds,
    - Turbulence
    - Sedimentation towards the plane of the disk.
- Observations → Angular Resolution & Sensitivity at long wavelengths are mandatory…

Dust evolution in protoplanetary disks

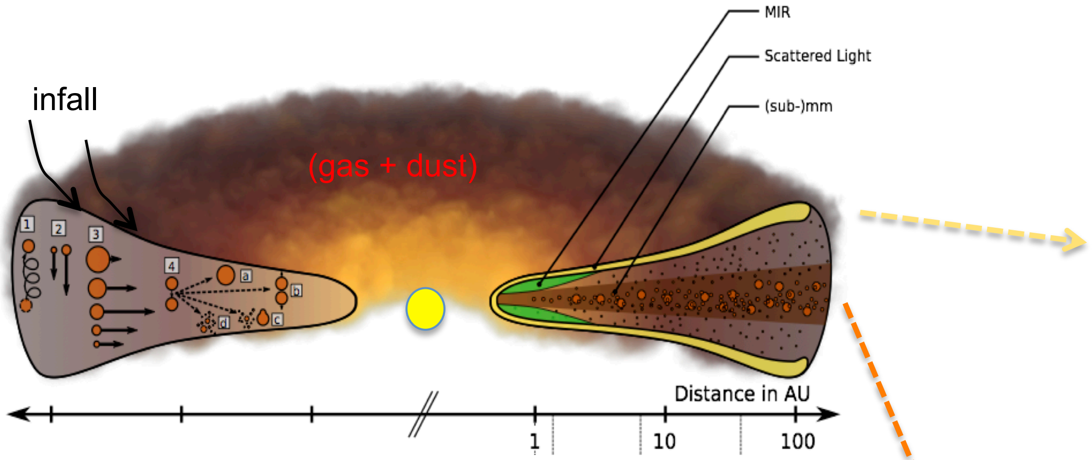


ALMA (1 mm)

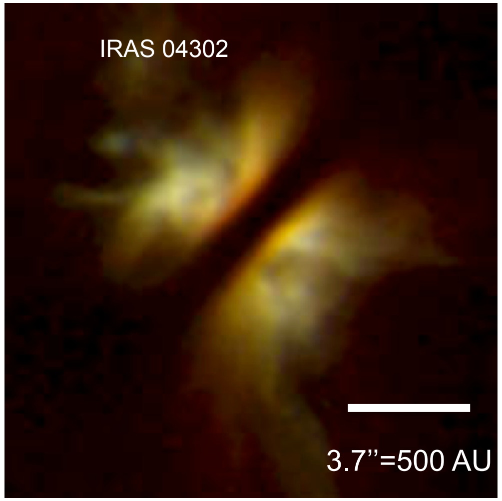


ALMA Patnership et al. 2015

Dust evolution in protoplanetary disks



HST (1-2 μm)



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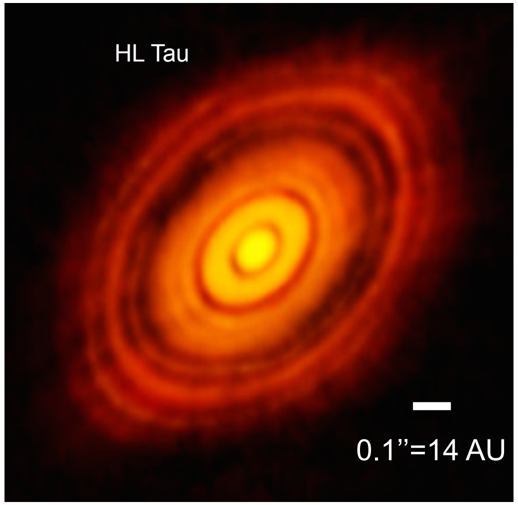
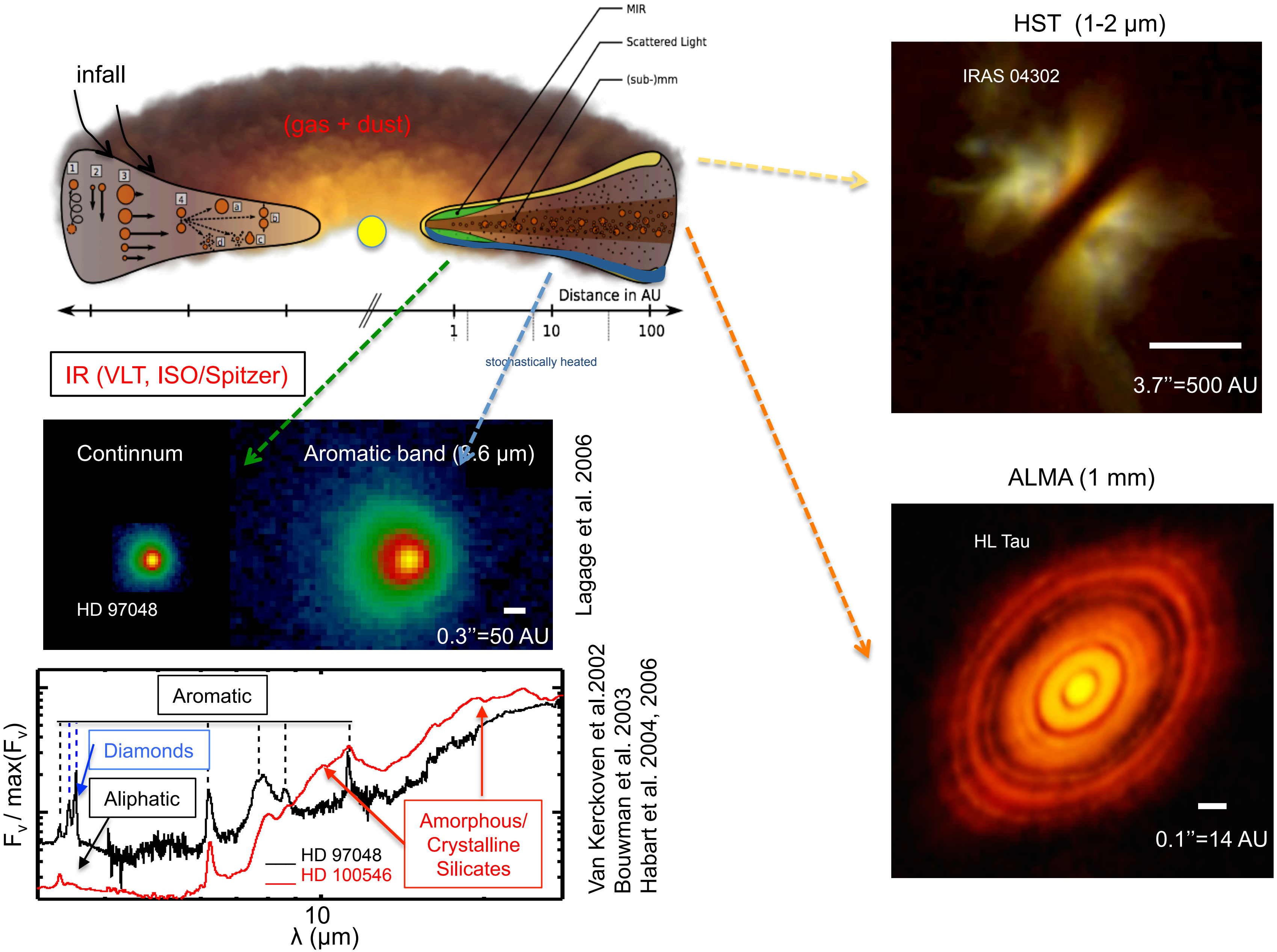


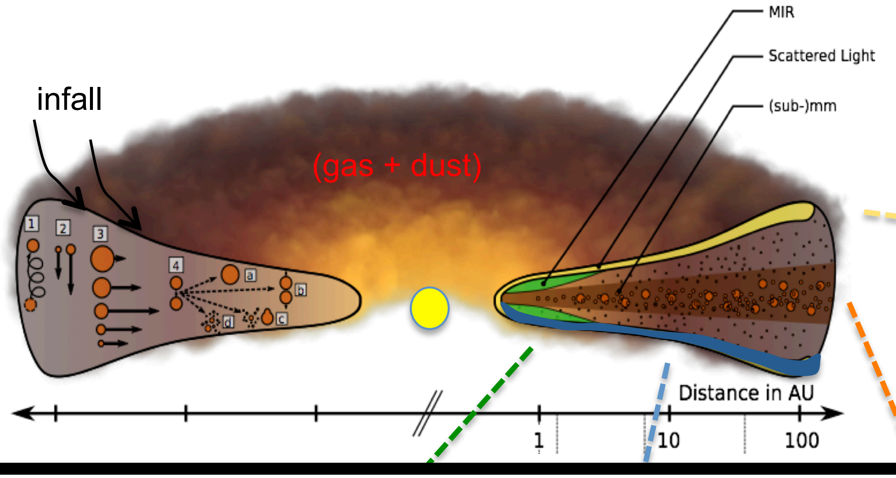
ALMA Patnership et al. 2015

Dust evolution in protoplanetary disks



ALMA Patnership et al. 2015

Dust evolution in protoplanetary disks



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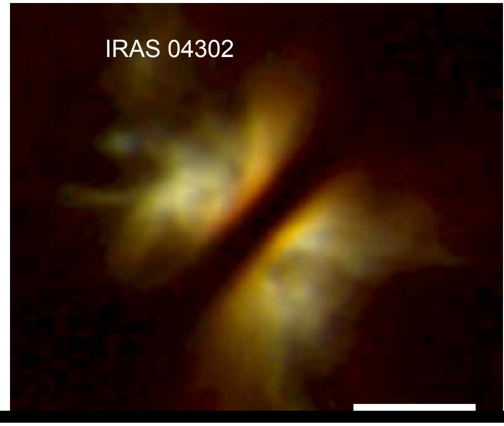
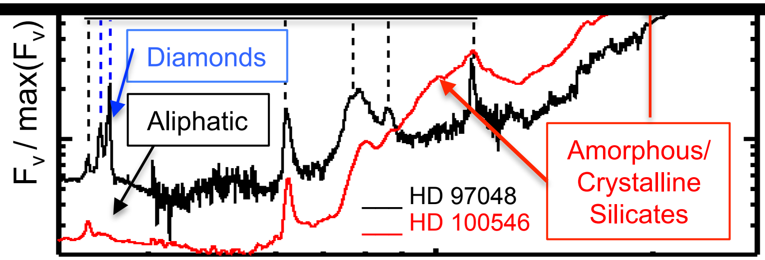
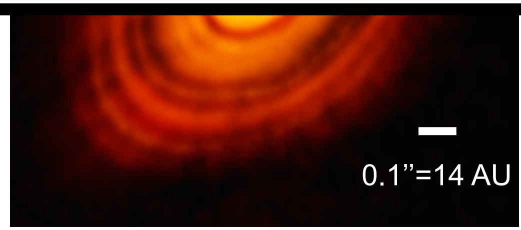


JWST : How dust properties change at the upper layers of the disks ?

- Spatially & spectrally-resolved dust emission and scattering with a unique sensitivity
- Only JWST can give the warm gas and dust inventory as a function of the local conditions.
- Unique access to large distance from the star (30-500 AU) and T Tauri stars (< 2 $M_{\odot}$)
- Dust evolution at the upper layers → Impacts on the growing processes



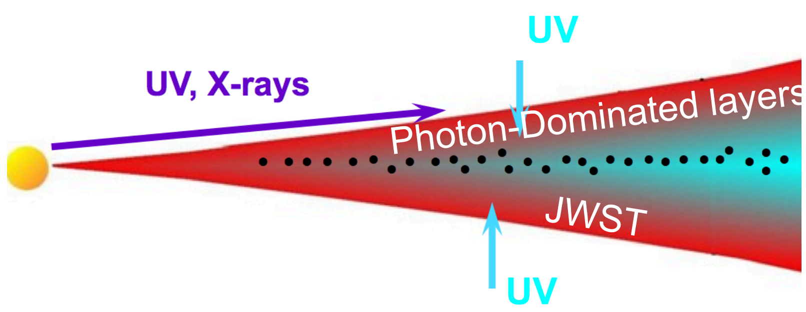
Van Kerckhoven et al.2
Bouwman et al. 2003
Habart et al. 2004, 20



ALMA Patner

WP3 (Modeling & Simulations) : PDRs & Disks

Disks: JWST signatures mainly from upper layers → Diagnostics comparable to PDRs



Task 1: Dust properties modeling
Task 2: Analysis of pre-JWST data
Task 3: Simulation of JWST observations
Task 4: Analysis of JWST observations

Strong interactions with laboratory experiments

Objectives:

- The modeling is the key to analyse the data:

  Realistic dust model in disks based on pre-JWST & JWST data, laboratory experiments

  Model calculations: dust (with adaptable properties) & radiative transfer,

  → Survival and interaction of nano-grains with UV photons at the illuminated edges

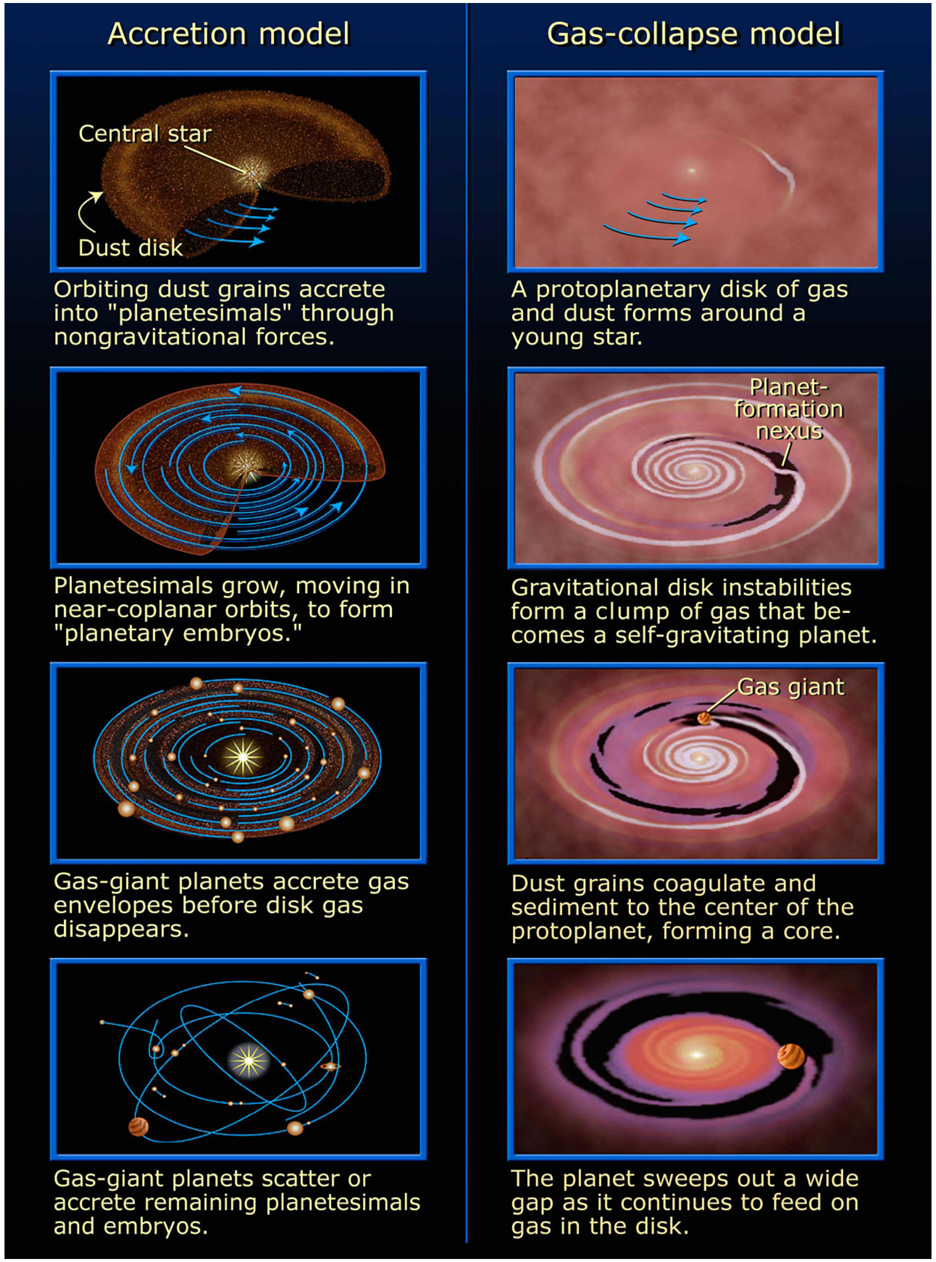
  → First coagulation of aggregates and settling phases

  → Constrain PDR/disk structures, which is essential for the study of the dynamics & chemistry

→ 2 PhD : 1 for disks and 1 for PDRs

Planet formation in disk : two scenarios

Accretion on planetesimals



Gravitational instability

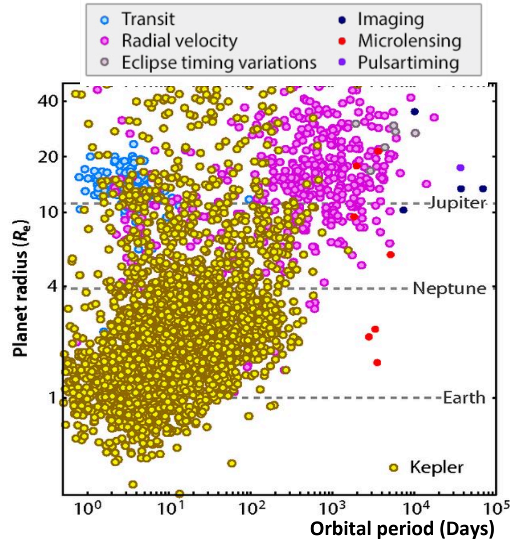
→ Self gravitating planet

Exoplanets

One of the fields in Astrophysics with the fastest growth :

→ Since 1995, more than **2000** exoplanets detected

→ Large diversity : Giant exoplanets not known in our solar system (hot Jupiters, inflated Jupiters, Super-Earths)



Today: Detection → **Characterization** aspect (known exoplanets)

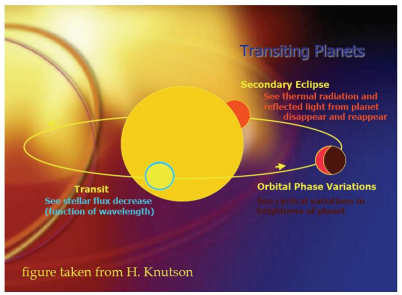
Atmosphere of giant planets with IR spectroscopy (Spitzer, HST, JWST)

Numerous molecular bands in the IR:

Molecule	$\Delta\nu = 2B_0$ cm^{-1}	λ (S_{max}) 2–5 μm	S_{max} cm^{-2} am^{-1}	R 2–5 μm	λ (S_{max}) 5–16 μm	S_{max} cm^{-2} am^{-1}	R 5–16 μm
H_2O	29.0	2.69 (ν_1, ν_3)	200	130	6.27 (ν_2)	250	55
HDO	18.2	3.67 ($\nu_1, 2\nu_2$)	270	150	7.13 (ν_2)		77
CH_4	10.0	3.31 (ν_3)	300	300	7.66 (ν_4)	140	130
CH_3D	7.8	4.54 (ν_2)	25	280	8.66 (ν_6)	119	150
NH_3	20.0	2.90 (ν_3)	13	170	10.33	600	50
		3.00 (ν_1)	20		10.72 (ν_2)		
PH_3	8.9	4.30 (ν_1, ν_3)	520	260	8.94 (ν_4)	102	126
					10.08 (ν_2)	82	110
CO	3.8	4.67 (1-0)	241	565			
CO_2	1.6	4.25 (ν_1)	4100	1470	14.99 (ν_2)	220	420
HCN	3.0	3.02 (ν_3)	240	1100	14.04 (ν_2)	204	240
C_2H_2	2.3	3.03 (ν_3)	105	1435	13.7 (ν_5)	582	320
C_2H_6	1.3	3.35 (ν_7)	538	2300	12.16 (ν_{12})	36	635
O_3	0.9				9.60 (ν_3)	348	1160

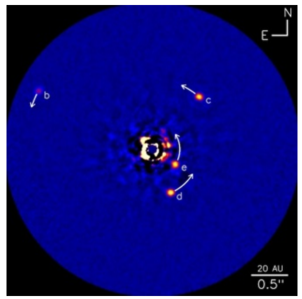
Table 5 Main molecular signatures and constraints on the spectral resolving power. $\Delta\nu$ is the spectral interval between two adjacent J-components of a band. S_{max} is the intensity of the strongest band available in the spectral interval. R is the spectral resolving power required to separate two adjacent J-components

The 1st key facility to study exoplanet atmosphere will be the JWST



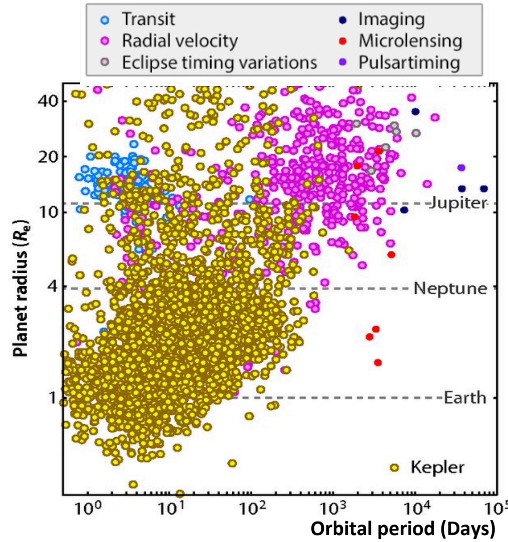
Transit

Decrease by factors 10^{-5}



Direct imaging

Exoplanets



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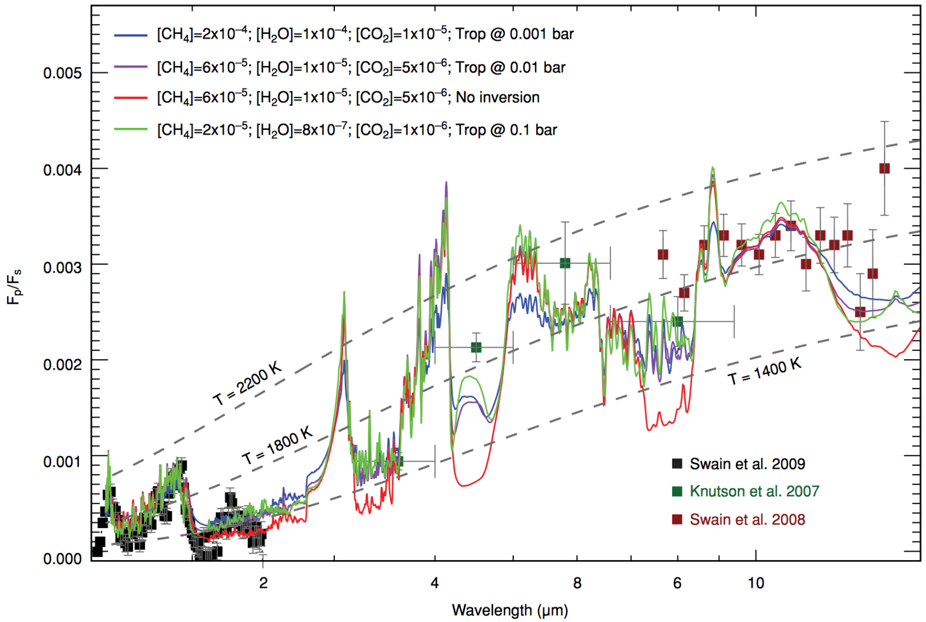
Today: Detection → **Characterization** aspect (known exoplanets)

Atmosphere of giant planets with IR spectroscopy (Spitzer, HST, JWST)

Only two exoplanet spectra (hot Jupiter) over the visible to mid-IR range (HST-Spitzer):



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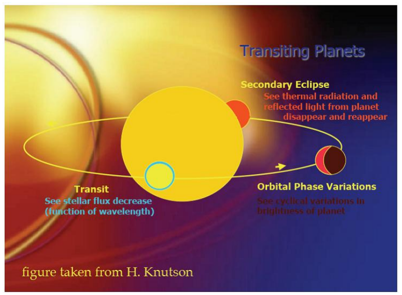

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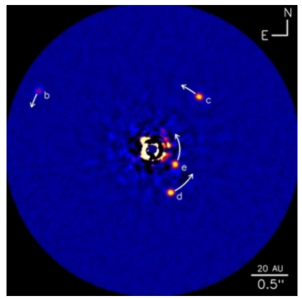


Direct imaging

WP3 (Modeling & Simulations) : Exoplanet atmospheres

→ Test of atmospheric models, circulation models, climate models in new regimes

→ Link Protoplanetary disks – Atmosphere of giant planets

C/O ratio in disks

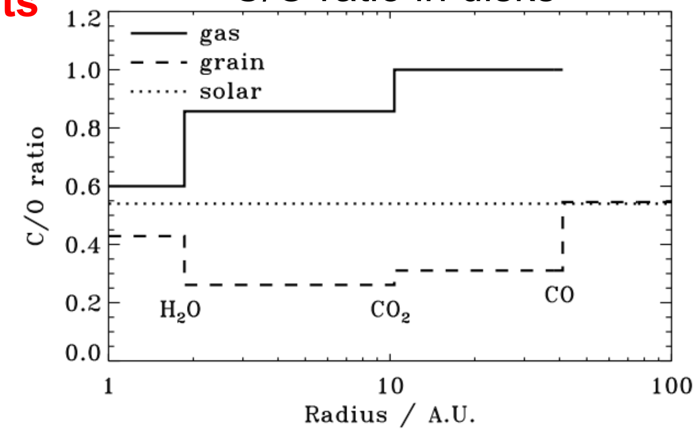


Fig. 1.— The C/O ratio in the gas and in grains, assuming the temperature structure of a 'typical' protoplanetary disk around a solar-type star (T_0 is 200 K, and $q = 0.62$). The H_2O, CO_2 and CO snow-lines are marked for reference.

Planetary formation starts with the coagulation of icy grains,
C/O ratio = '' f ''(place where the exoplanet forms in the disk)
(due to different $T_{condensation}$ for H_2O, CO_2 & CO)

Comparison with the C/O value of the central star
→ discriminate between different formation models

To retrieve the C/O ratio from IR JWST spectra
→ **Need models** (with radiative transfer, opacities…)
- 1D exoplanet atmospheric model of Paris-Saclay (ATMO), one of the best models at the international level

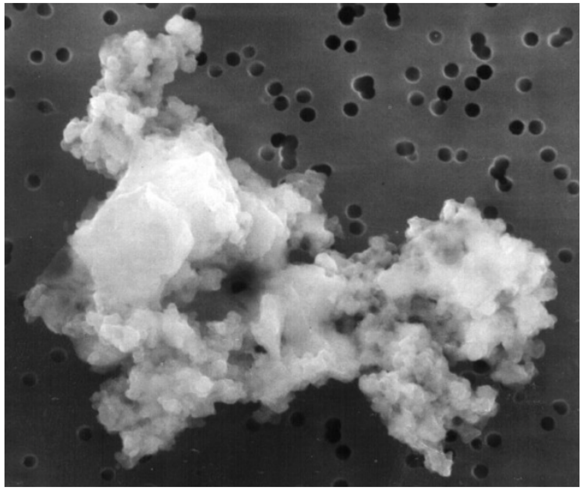
Task 1: Benchmarking
Task 2: Effect of composition variations
Task 3: Include dust clouds (relation with the dust expertise from WPs 3 & 4)
Task 4: 3D models to assess the uncertainties when using 1D model
Task 5: Analyse first JWST observations

→ 1 two year post doc

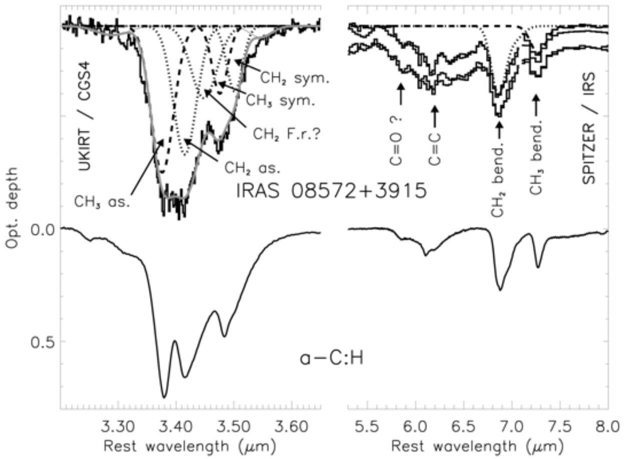
Laboratory experiments : why ?

Nature of interstellar grains ?

Complexity of astrophysical IR spectra

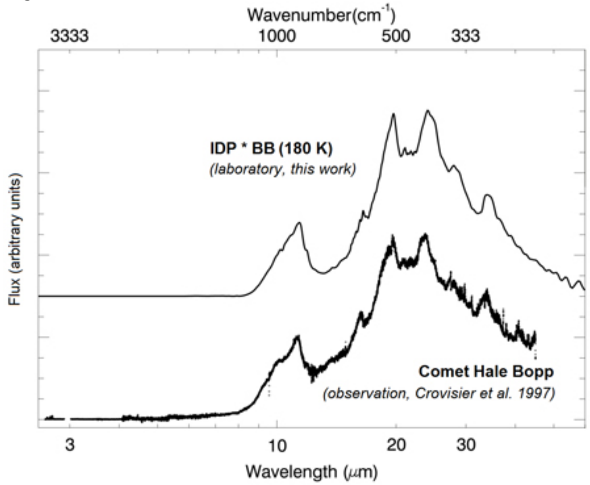


IDP (NASA/JPL)



Analogues

Dartois et al. 2007



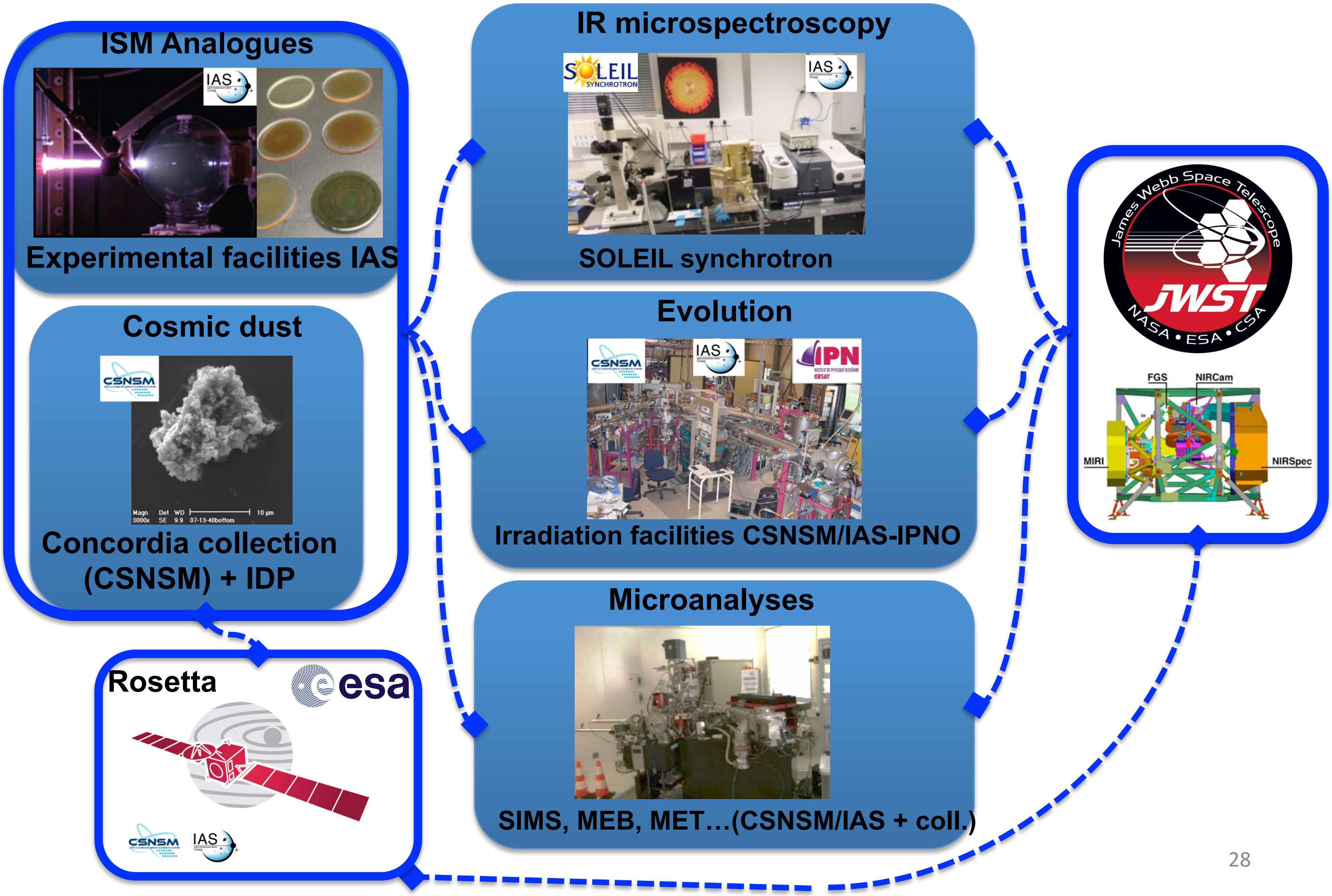
IDP

Brunetto et al. 2011

Laboratory experiments are essential:

- → for direct comparison with observational data
- → to provide experimental data for modeling
- → to understand the nature and the effects of radiative processes

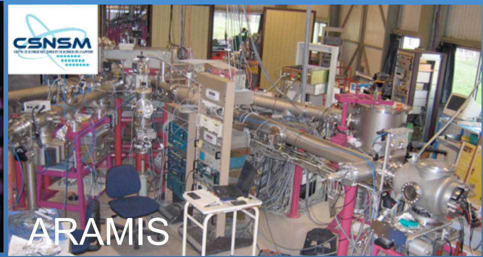
Laboratory experiments in P2IO laboratories



WP4 Laboratory experiments: Organic Matter

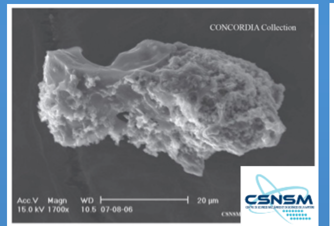
Origin of organic matter : link ISM – protoplanetary disk?

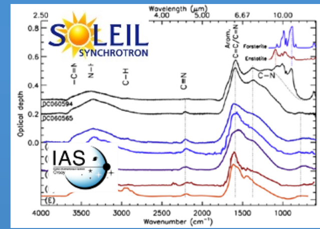
Task 1: ISM analogues a-C:H doped in N & O (IAS/CSNSM)

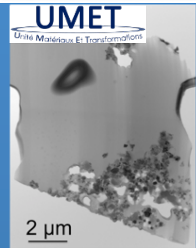


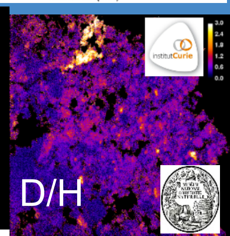
Task 2: Study cometary matter

- CONCORDIA dust collection CSNSM

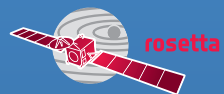


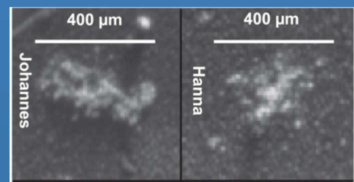




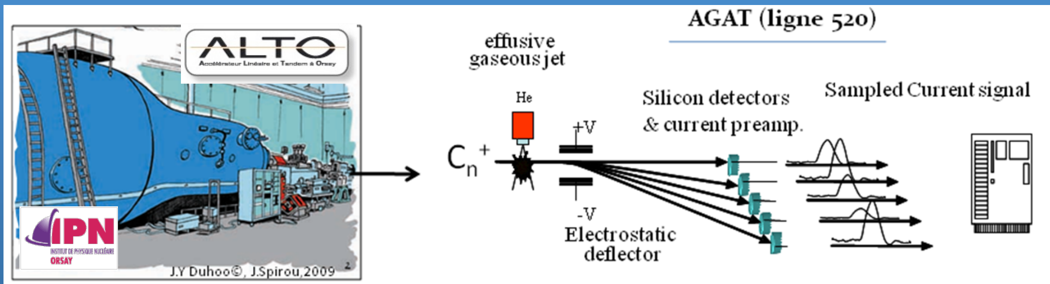


- Rosetta/COSIMA





Task 3: Physico-chemistry in the ISM : irradiation - released species in the gas (IPNO ALTO, CSNSM ARAMIS, CSNSM/IAS Astroline SIDONIE,…)



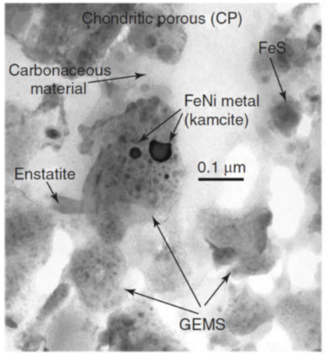
Task 4: Synthesis and preparation of interpretation of JWST data

→ **1 two year postdoc already funded by P2IO**

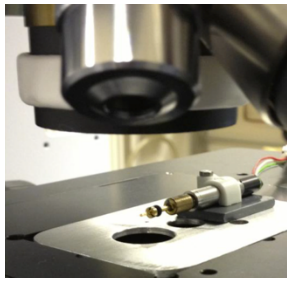
WP4 Laboratory experiments: Silicate Matter

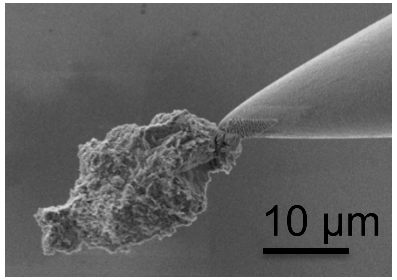
IR spectroscopy of primitive extraterrestrial material

Task 1 and 2: IR spectra of bulk and µm sub-units of meteoritic materials

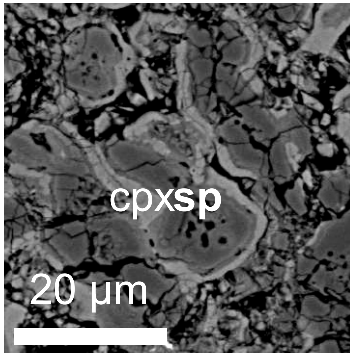


Task 3: 3D IR micro-tomography : porosity of grains

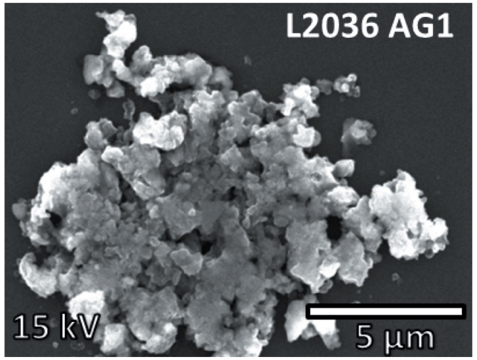




Troadec et Aléon-Toppani, 2015

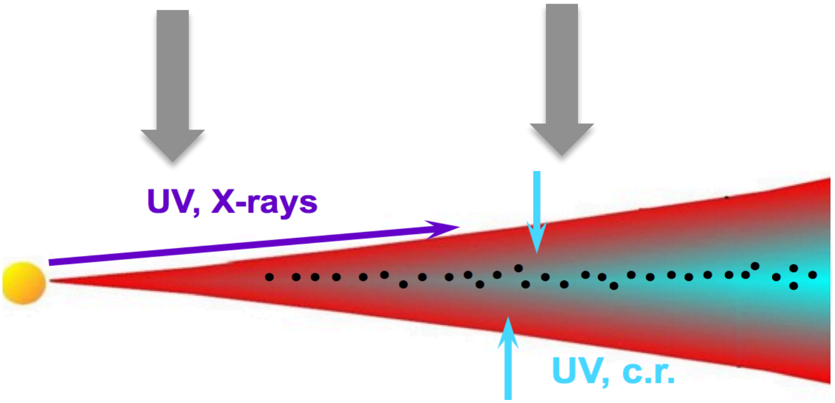


CAI



IDP

Merouane et al., 2014



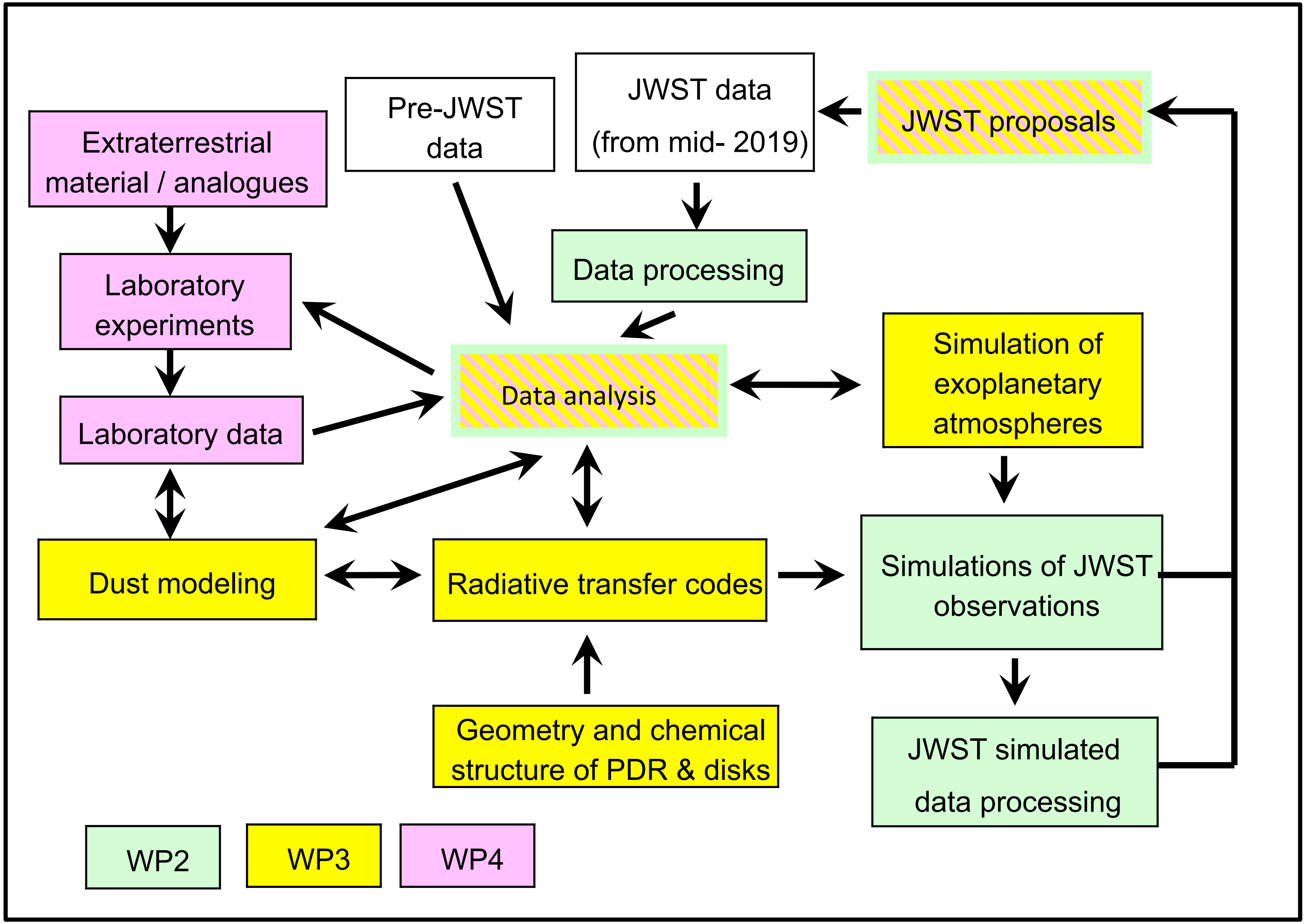
Task 4: Irradiation experiments in disk conditions
IAS, CSNSM

Task 5: Comparison with pre-JWST & JWST data

- Crystallinity/amorphous and olivine/pyroxene ratios in the disk
- GEMS and CAIs in disks
- Hydrated silicates vs water vapor ?

→ 1 PhD

Organisation chart



Conclusions & Success Criteria

Put together the strong expertises in several P2IO laboratories on :

- **Interstellar matter - physical and chemical evolution** (IAS, SAp/AIM)
- **Protoplanetary disks** (SAp/AIM, IAS)
- **Exoplanets** - modeling of their atmosphere & observations (SAp/AIM, IAS)
- **Laboratory analyses** of extraterrestrial matter and analogue materials (CSNSM, IAS, IPNO), with access to large facilities (SOLEIL, ALTO-Tandem, Aramis/SIDONIE)
- **Long wavelengths instruments**: ISO, Planck, Herschel, MIRI/JWST (SAp/AIM, IAS)

→ Multi-disciplinary and Multi-laboratory P2IO team for the scientific exploitation of the JWST (2019→2030)

- 3 two year post-doc
- 4 PhD (2 ½ PhD funded by our P2IO project)

→ Prepare young astrophysicists to work on JWST data