A NenuFAR Key Program to study the feedback of stars on the interstellar medium of galaxies

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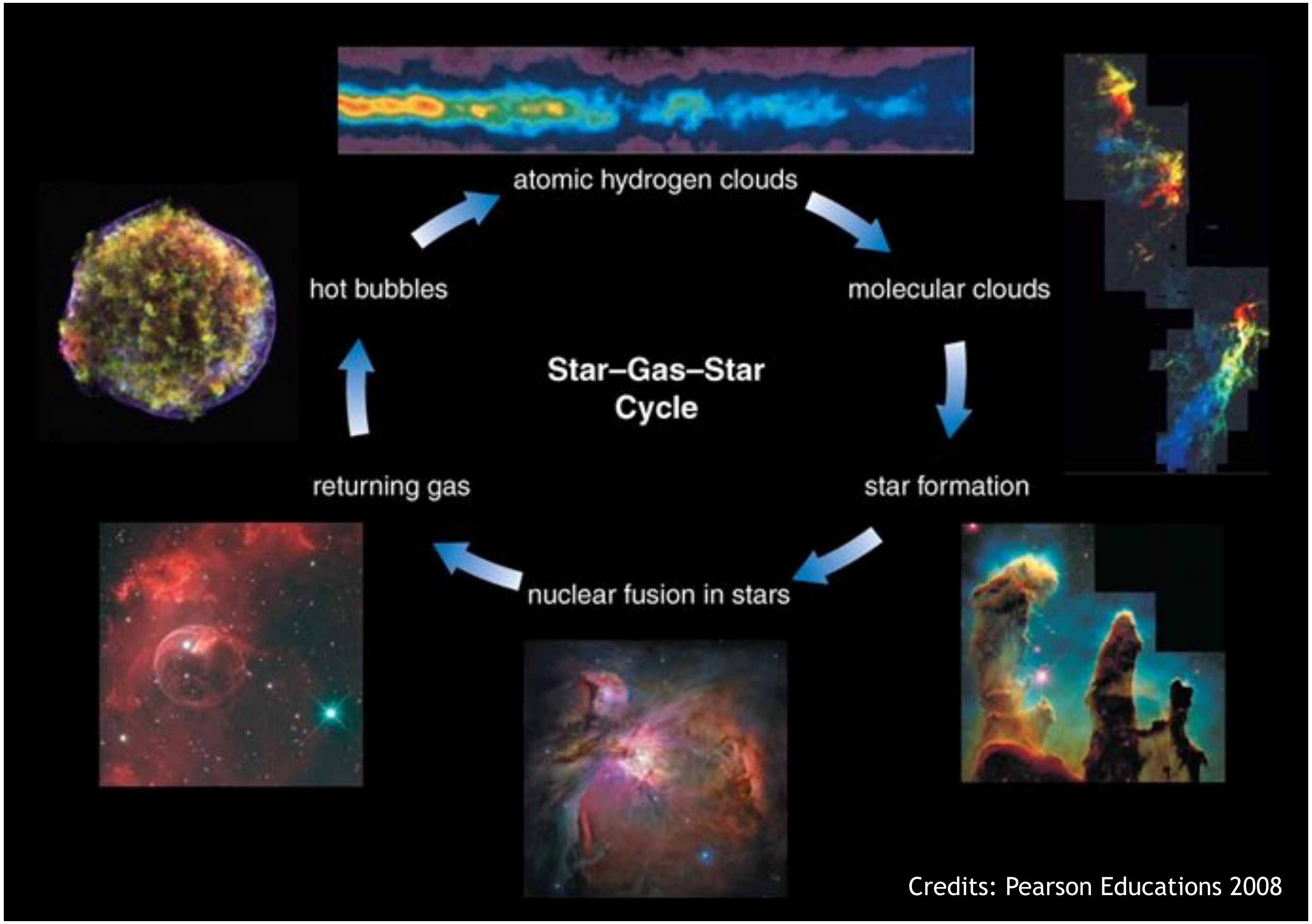
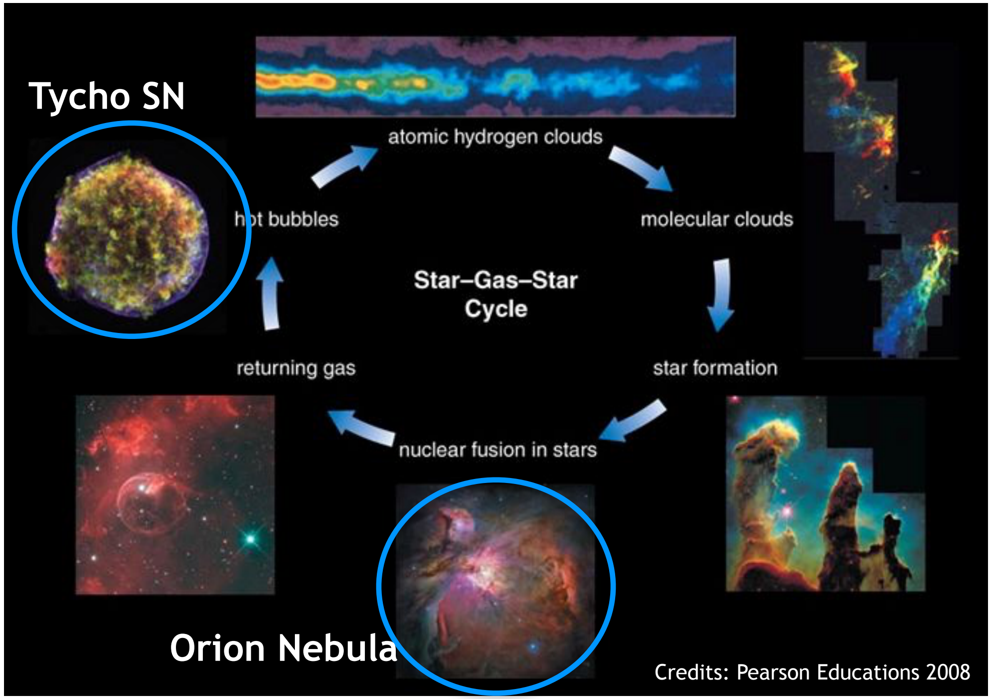
Interstellar medium (ISM) of galaxies

ISM: gas and dust (matter), cosmic-rays, and magnetic fields.
Structure, physical and chemical properties of the ISM control star formation.



Stellar feedback on the ISM

Stellar feedback (radiation, stellar winds, HII regions, SN explosions…) changes the structure of the ISM and its physical and chemical properties.



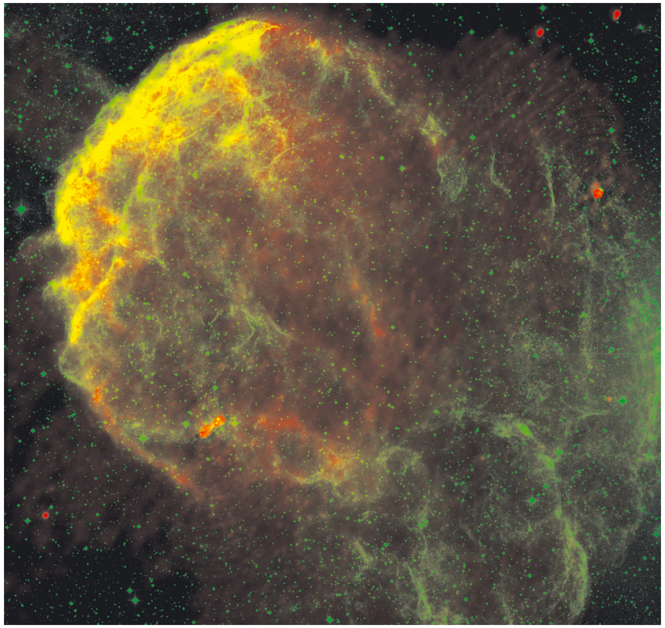
This has a direct impact on the next generation of stars.

Need to understand and characterise stellar feedback to understand and model the whole process of star formation.

Stellar feedback on the ISM: shocks & PDRs

Two prime environments dominated by stellar feedback extensively studied observationally and theoretically: shocks and photodissociation regions (PDRs).

IC 443 supernova remnant (SNR)



Optical (green, Palomar) & radio 330 MHz (red, VLA); Castelletti et al. (2011)

M42 HII region

Hubble optical image (NASA)

We will focus on these two environments in this KP.

Concept

- Developing sophisticated codes to model the physics and chemistry of the ISM of galaxies is a French speciality. These codes are used to interpret observations of the ISM by numerous teams all over the world.

- The **Paris-Durham shock model** simulates the propagation of shock waves in the ISM (a few km/s to a few 10 km/s).

- The **Meudon PDR code** calculates the structure of regions where the far-ultraviolet photons emitted by massive stars drive the physics and chemistry of the medium.

- Both codes are used to quantify the feedback of stars on the ISM of galaxies and two parameters are key to the study of numerous related questions:
  - The electron density $\mathbf{n_e}$
  - The magnetic field **B**

- **Low frequency radio observations provide innovative means to constrain these parameters. We want to learn how to master these means with you.**

What is the goal of this NenuFAR KP?

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(1) Observe **radio recombination lines** (RRLs of H and C) towards stellar feedback-dominated regions (shocks & PDRs) to derive physical properties of ionised gas (density, temperature, size of the cloud, …).

Work in collaboration with model experts not only to use models to interpret observations but also because modellers want to include treatment of RRLs in their codes.

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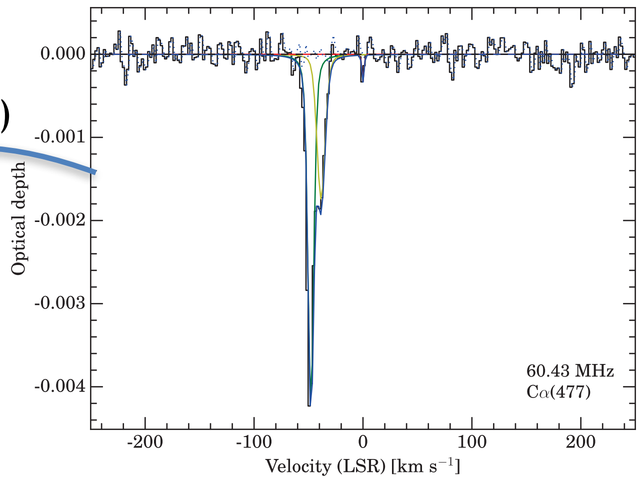
C RRL models (level population, Salgado et al. 2017)

n_e, B, L



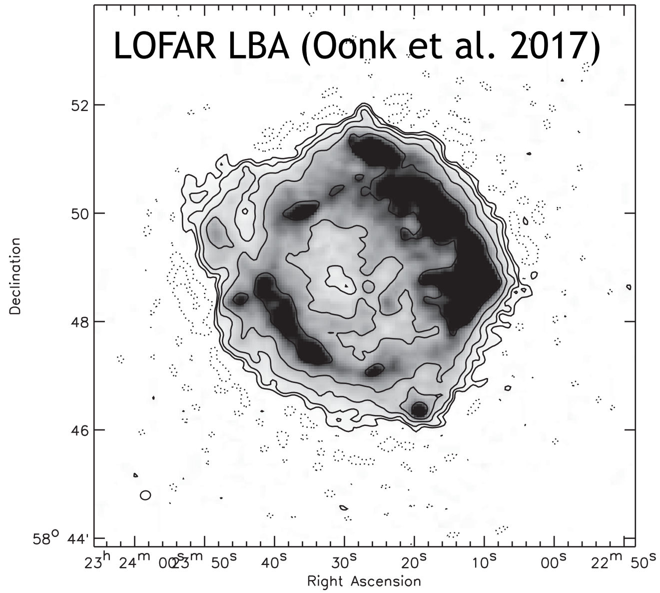


Figure 1. Cas A continuum image at 69 MHz obtained from a single 0.2-MHz subband. This image was made from a LOFAR LBA observation, taken on 2011 October 15, using uniform weighting and has a resolution of 11.2 × 9.8 arcsec^2.

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(2) The magnetic field is the less exploited ingredient in the ISM; its impact in the structure and properties of shocks & PDRs its potentially important and has been poorly studied.

NenuFAR will give us $\mathbf{n_e}$; this is required to derive **B** from Faraday rotation (tomography) observations that are proportional to $\mathbf{n_e} \times \mathbf{B}$. These observations are readily available/possible with LOFAR (maybe NenuFAR?).

What's next

- A few more questions that our project will address
- The modelling teams and the user communities in France
- Possible targets for a NenuFAR KP
- Observational needs and ideas
- Conclusions

A few more questions that our KP will address

What are the physical mechanisms at work?

- For shock studies:

What is the type of shocks ? If stationary: C-, J-, C*-, or CJ-type ?

⇒ For all these questions, paramount importance of $\mathbf{n_e}$ and **B**; the magneto-sonic velocity (critical velocity discriminating C- and J-type shocks) is proportional to $\mathbf{B_{perp}}/[\rho_i]^{1/2}$ ($\mathbf{B_{perp}}$ magnetic field perp to shock direction, ρ_i is the mass density of the ionised fluid)

- For shock and to a lesser extent for PDR studies:

What is the role of **B** on the thermal structure of the region?

⇒ What is its influence on the heating/cooling balance ?

- For shock and for PDR studies:

What is the role of electrons in the thermal structure of the region?

⇒ Electrons collisionally excite other species so $\mathbf{n_e}$ is needed for radiative transfer

⇒ Electrons and neutrals interact so $\mathbf{n_e}$ is needed for ambipolar diffusion heating

- For PDR and to a lesser extent for shock studies:

How strong is the FUV-irradiation ? (Are the observed shocks irradiated)

⇒ Any measure of $\mathbf{n_e}$ will help, as FUV photons dissociate and ionise the medium

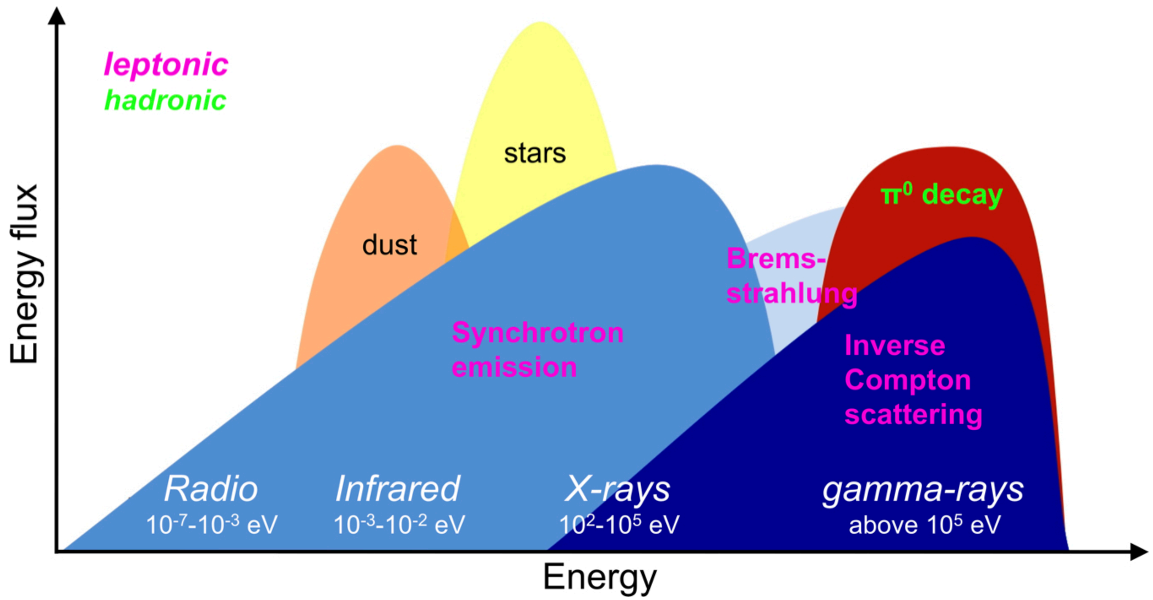
What is the chemical impact of shocks and PDRs ?

- **n_e** and **B** are key ingredients for both gas-phase chemistry and grain processing (grain-grain and gas-grain interactions releasing the products of grain chemistry in the gas phase):
  - Thermal effects linked with **n_e** and **B** unavoidably affect the chemistry (endothermic reaction barriers can be overcome or not)
  - Ambipolar diffusion that they control is key to reactive and non-reactive collisions between ions and neutrals, whether these are gas phase species or grains

Can we characterise cosmic ray (CR) properties?

- Our understanding of CR properties (acceleration mechanisms, composition, diffusion) mostly relies on interpretation of gamma-ray emission, produced by interactions between CRs and the local medium:
  - Hadronic CRs (=protons) + the dense medium = π^0 decomposition
  - Leptonic CRs (=electrons) + magnetic field = synchrotron emission
    + the dense medium = Bremsstrahlung
    + photons = inverse Compton scattering

RRLs give (**n_e**, **T_e**) but also CR ionisation rate. **B** is of course a crucial parameter for CR studies — also collaborating with CR community.



The modelling team and the user communities in France

Shock models — developments in France

- The Paris-Durham shock model (created in 1985):
  - LERMA – OP team: S. Cabrit, G. Pineau des Forêts

  (since 2008: D. Panoglou, S. Anderl, W. Yvart, B. Tabone, M. Rabenanahary)
  - LERMA – Meudon team: J. Le Bourlot, E. Roueff
  - LPENS Paris: B. Godard (LERMA), A. Gusdorf, P. Lesaffre

  (since 2008: S. Anderl, F. Louvet, A. Lehmann, P. Dell'Ova, M. Rabenanahary)
  - IAS Orsay: V. Guillet, A. Jones

  (since 2008: S. Anderl)

- A Photo-evaporating model (with the Hydra PDR code):
  - LERMA – Meudon team: E. Bron

- Mappings III (fast radiative shock models):
  - Strasbourg Observatory: M. Allen

Users of the Paris Durham model in France (1)

- Protostellar jets and outflows:
  - LERMA – Paris team: S. Cabrit, G. Pineau des Forêts, B. Tabone
  - LPENS – Paris: B. Godard (LERMA), A. Gusdorf, A. Lehmann, P. Lesaffre, M. Rabenanahary
  - IPAG – Grenoble: B. Lefloch (CHESS, ASAI, SOLIS)
  - IPAG – Grenoble: F. Motte, F. Louvet & T. Nony (LP ALMA-IMF)

- Supernova remnants & link with very high energy community:
  - LPENS – Paris: A. Gusdorf & P. Dell'Ova
  - AIM – Saclay: F. Acero, I. Grenier
  - LUPM – Montpellier: A. Marcowith
  - APC – Paris: S. Gabici
  - CENBG – Bordeaux: M. Lemoine-Goumard

Users of the Paris Durham model in France (2)

- Cloud-cloud collisions:
  - IPAG – Grenoble: F. Motte, F. Louvet & T. Nony (LP ALMA-IMF)
  - LAB – Bordeaux: N. Brouillet, D. Despois & *J. Molet* (LP ALMA-IMF)
  - LAB – Bordeaux: S. Bontemps & L. Bonne (ANR GENESIS)

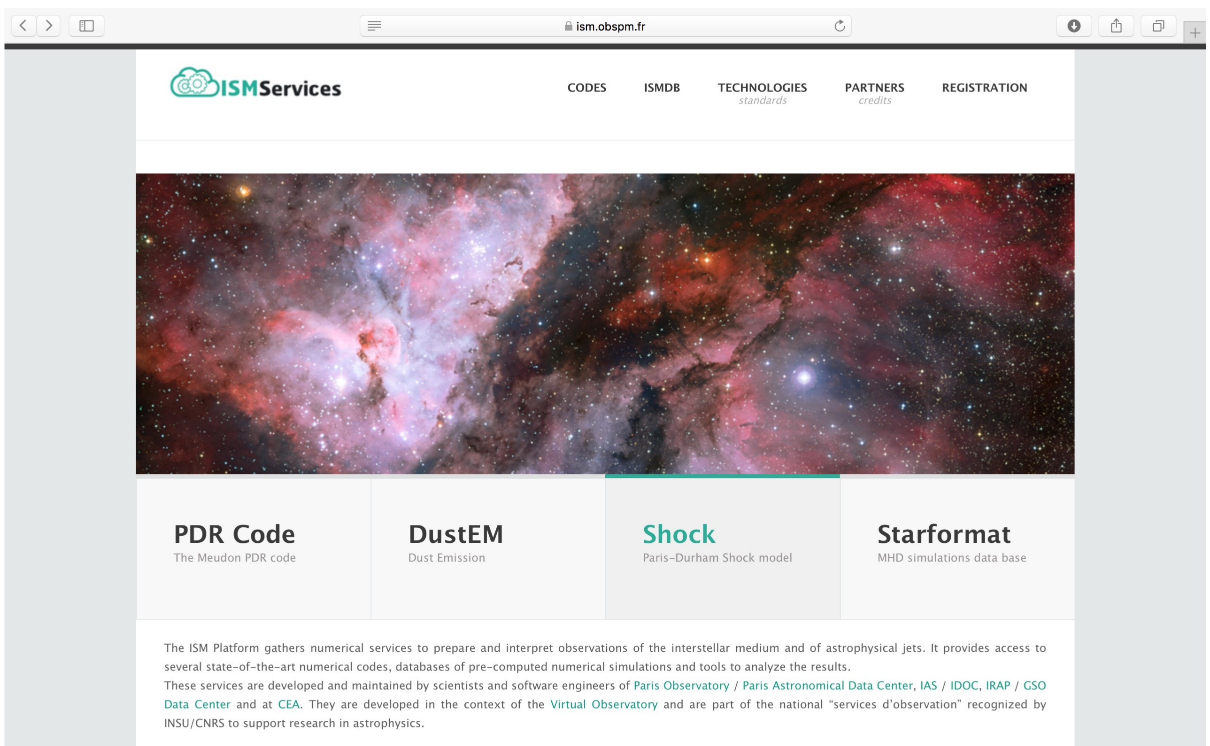
- Extragalactic environments:
  - LERMA – Paris team: P. Salomé (& ANR LYRIX team), Q. Salomé, F. Combes
  - LPENS – Paris: E. Falgarone (& ERC MIST team)
  - AIM Saclay: S. Madden & team
  - IAP - Paris: P. Guillard, M. Lehnart

- Other environments:
  - IRAP – Toulouse: O. Berné & J. Champion, PROPLYDs
  - LAB – Bordeaux: A. Dutrey, S. Guilloteau & team, accretion shocks
  - LAB – Bordeaux: N. Brouillet, D. Despois & J. Molet (LP ALMA-IMF)

The Meudon PDR code

- The Meudon team (Le Bourlot et al. 1993):
  - LERMA – Meudon team: J. Le Bourlot, E. Bron, F. Le Petit, E. Roueff
  - LPENS Paris: B. Godard (LERMA)

- For both codes (PDR and shock), online access and tools are available via: https://ism.obspm.fr, also developed by D. Languignon, N. Moreau, C.-M. Zwölf



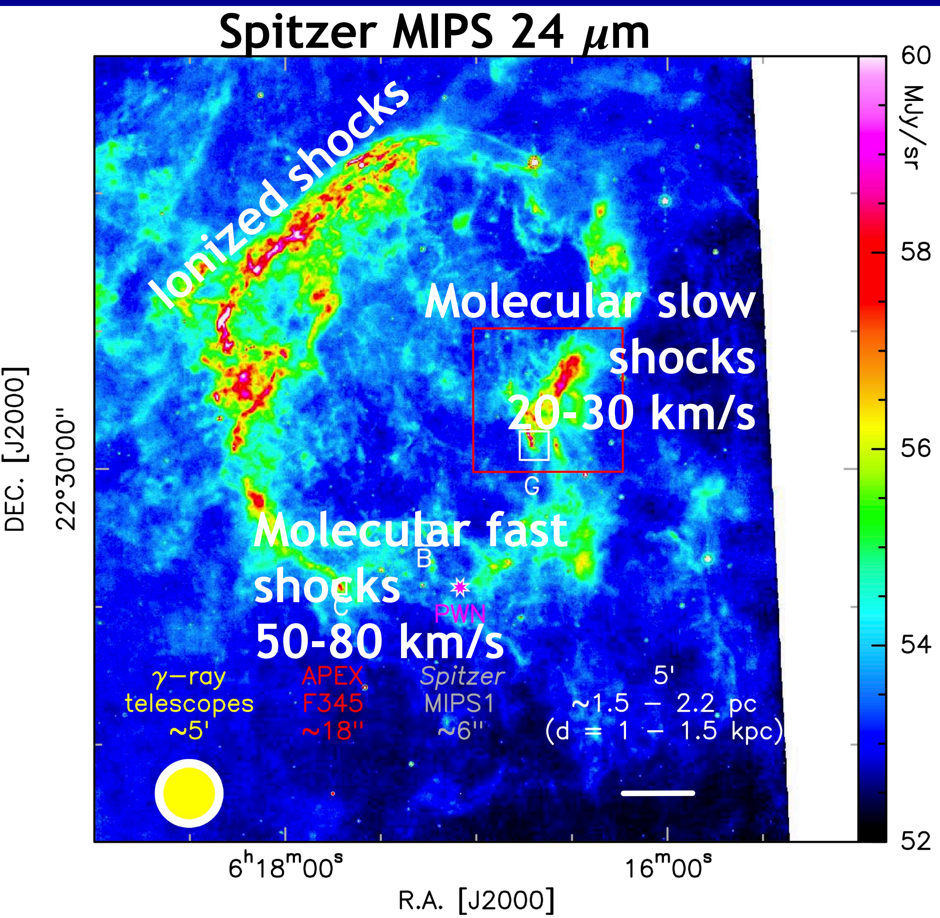
Users of the Meudon PDR code in France

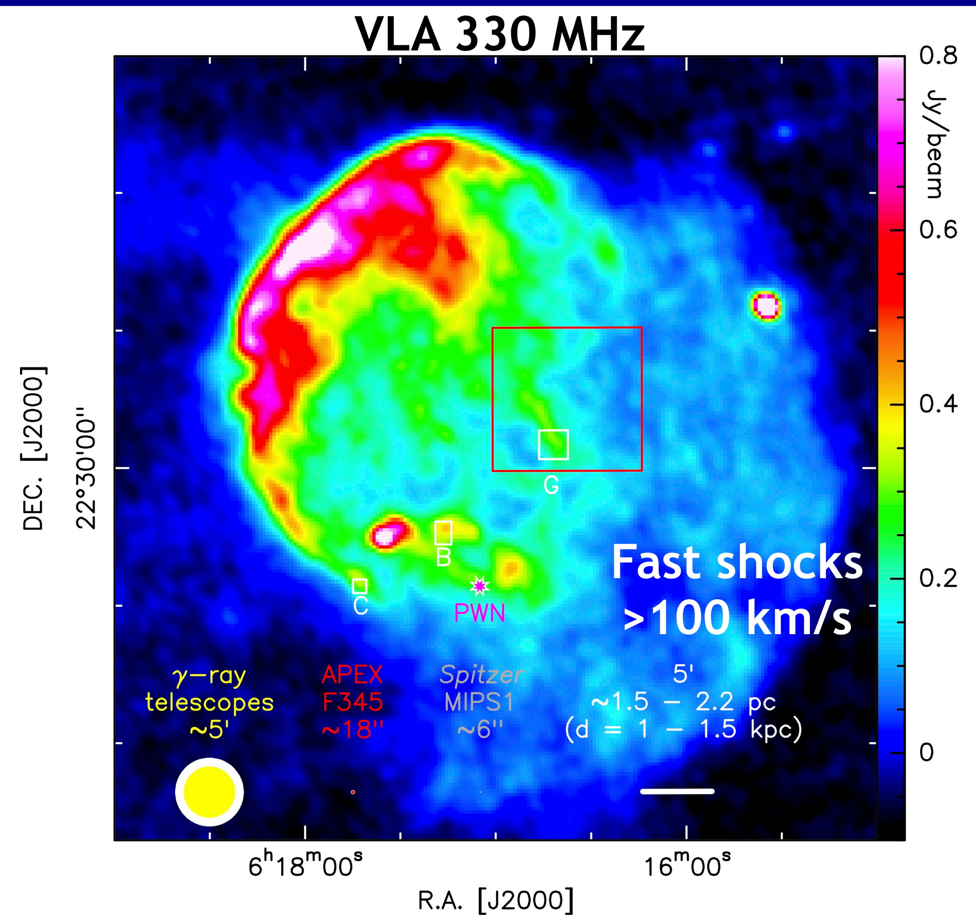
- Dust studies:
  - IAS – Orsay: E. Habart, L. Verstraete, N. Ysard
  - IRAP – Toulouse: O. Berné, C. Joblin, I. Ristorcelli

- ISM studies:
  - LAB – Bordeaux: P. Gratier, V. Wakelam
  - LPENS – Paris: F. Levrier, F. Boulanger
  - AIM Saclay: S. Madden & team
  - IRAM Grenoble: J. Pety

Possible targets for a NenuFAR Key Program

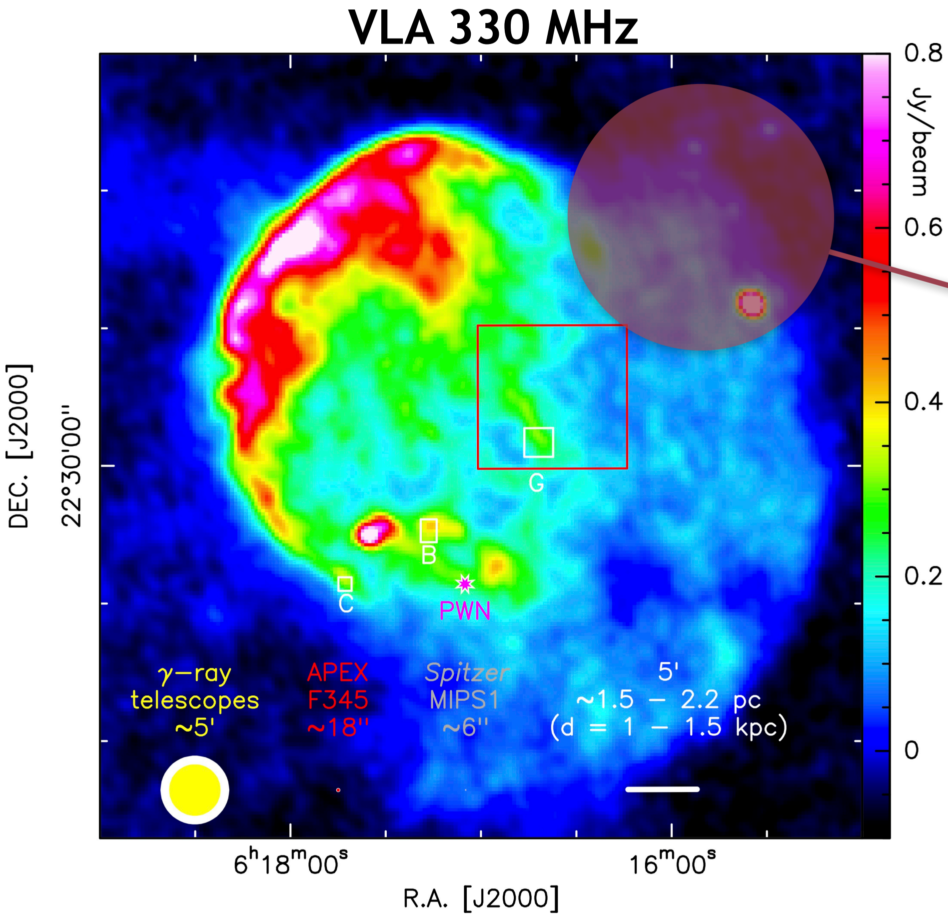
(1) Shocks: IC 443 SNR





- Ideal laboratory for many studies:
  - Shock studies – **variety of shock conditions probed around the shell(s)**
  - Star formation studies
  - Cosmic rays studies
  - Well suited size for proof of concept studies (~1° across, d=1.2 kpc)

(1) Shocks: IC 443 SNR



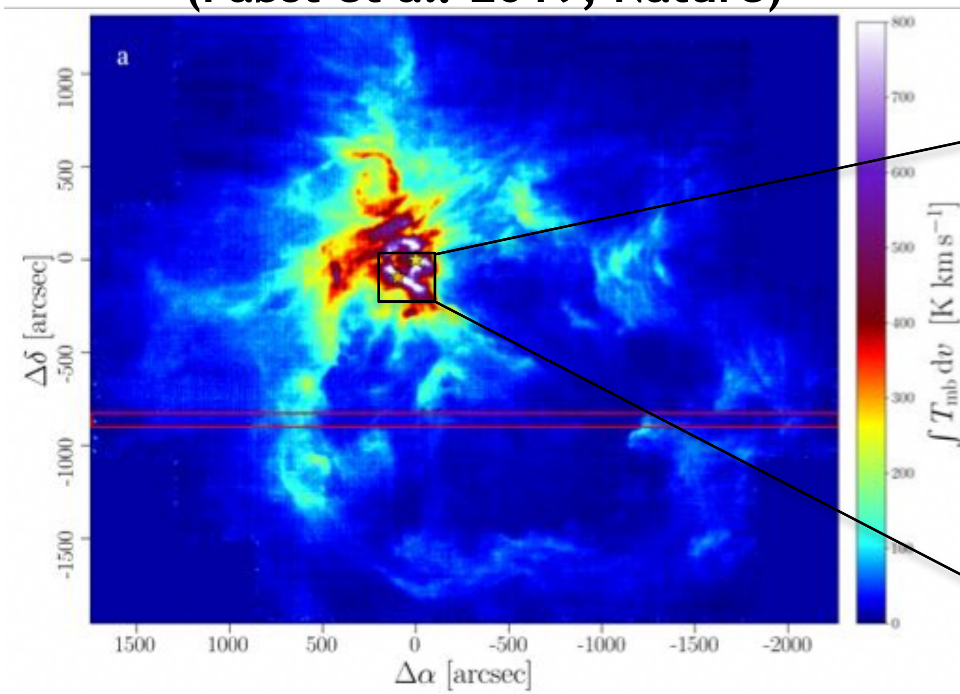
NenuFAR beam ~ 20’
(core + 4 remote stations)

FoV > size of object

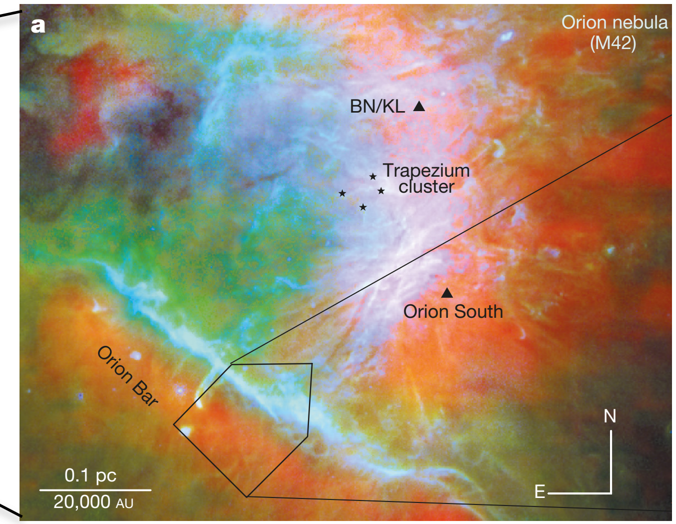
Notes:
(i) LOFAR LBA Cycle 0 RRL data available (good to cross-check).
(ii)LOFAR HBA LoTSS Faraday tomography data available in a couple of weeks.

(2) PDRs: Orion Bar

[CII] (SOFIA) integrated emission (Pabst et al. 2019, Nature)



ALMA + VLT/MUSE (Goicoechea et al. 2016, Nature)



- Probably the most observed and modelled region/PDR (d=414 pc)!

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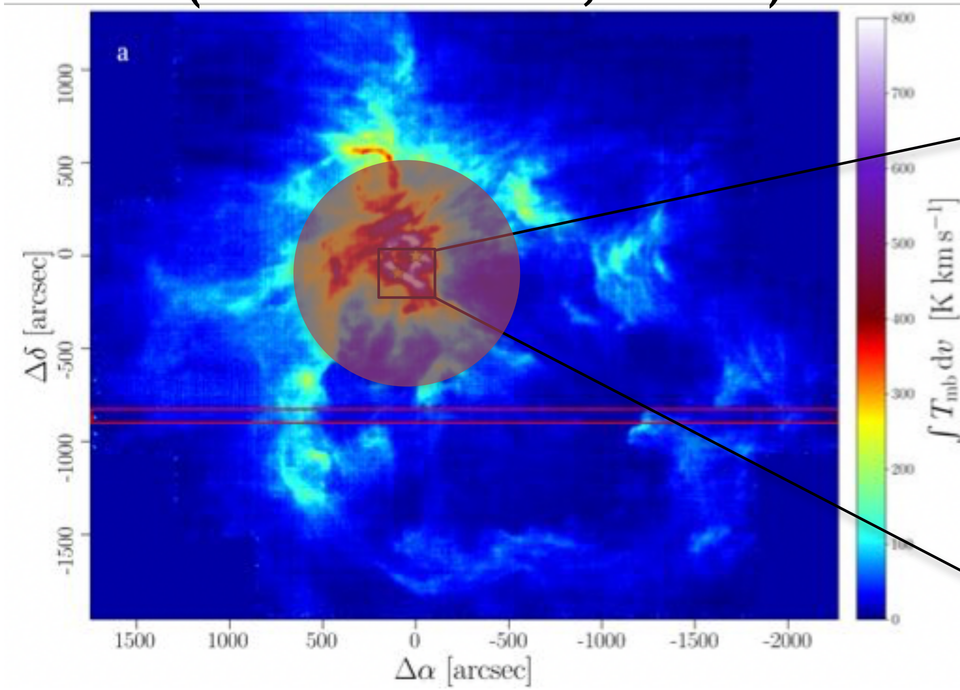

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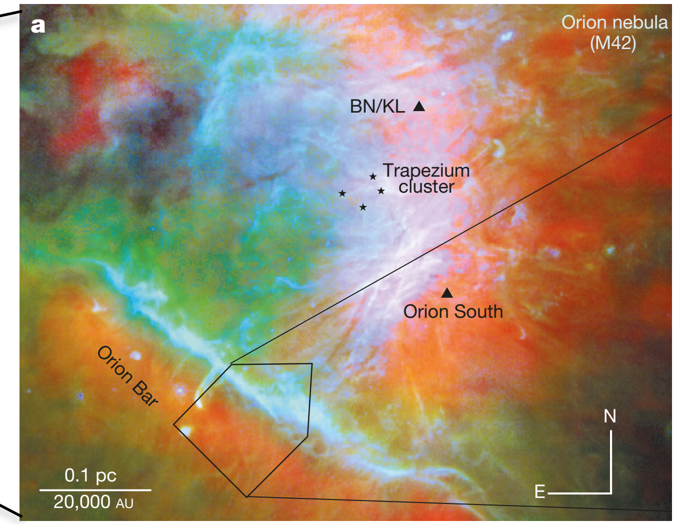

- Probably the most observed and modelled region/PDR (d=414 pc)!
- **But PDRs are small!!** Can start by characterising diffuse gas.

Notes:
(i) Similar ongoing RRL study with LOFAR and other data (VLA, GMRT, etc) covering the whole nebula (A. Tielens); no LBA data yet available.

Observational needs/help!

The data that we need

- We need images (**imaging mode**); ideally of the whole object (when extended w.r.t. beam); at each channel across the whole 10—88 MHz band — **data cubes**.

  Maybe we can start with a couple of pointings?

- We want the best angular resolution possible. (It will get better after all remote stations are installed.)

  Maybe eventually use LSS mode for PDR studies?

- We want the best spectral resolution possible: 3 kHz (64 chan/195 kHz band) is not ideal since it's comparable to the width of the lines…

  Can we play around with number of beams to gain in spectral resolution?

- No other observational constraints.

Total requested time?

- Still need to estimate line temperatures for each source; then use the tools presented yesterday to estimate observing time.
- We propose two objects but we have other possible targets in mind: other SNRs (e.g. W44), cloud-cloud collisions shocks, galaxy groups with shocks, other PDRs.
- First check integration time for two proposed objects before aiming for more? Also because we want to use the imager, which will be available later during the early science phase.
- (After all this need to evaluate total data volume.)

Conclusions

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Our project:

- Observe **radio recombination lines** (RRLs of H and C) towards stellar feedback-dominated regions (shocks & PDRs) to derive physical properties of ionised gas (density, temperature, size of the cloud, …).
- Work in collaboration with model experts who want to include RRL physics in codes.

Synergies:

- VERITAS/Fermi/CTA – CR physics
- LOFAR – magnetic field from Faraday tomography
- SOFIA (NASA stratospheric plane) and GUSTO (NASA ballon) – cooling rate and photoelectric heating rate from [CII] emission
- SKA – our project is a flavour of what the SKA will be able to do