STARFORMAT
a platform of numerical simulation results and tools for star formation

François LEVRIER
Ecole Normale Supérieure de Paris

Astrophysics Colloquium
University of Oxford
22 February 2011

Overview of the talk

The project

- Scientific context and questions
- Overview of the project
- Structure of the database

An example simulation : converging flows

- Accessing simulation results
- Statistics of "clumps" and comparison with observational data
- On-the-fly clump extraction
- Post-processed radiative transfer with RADMC-3D
- The other simulations in the database

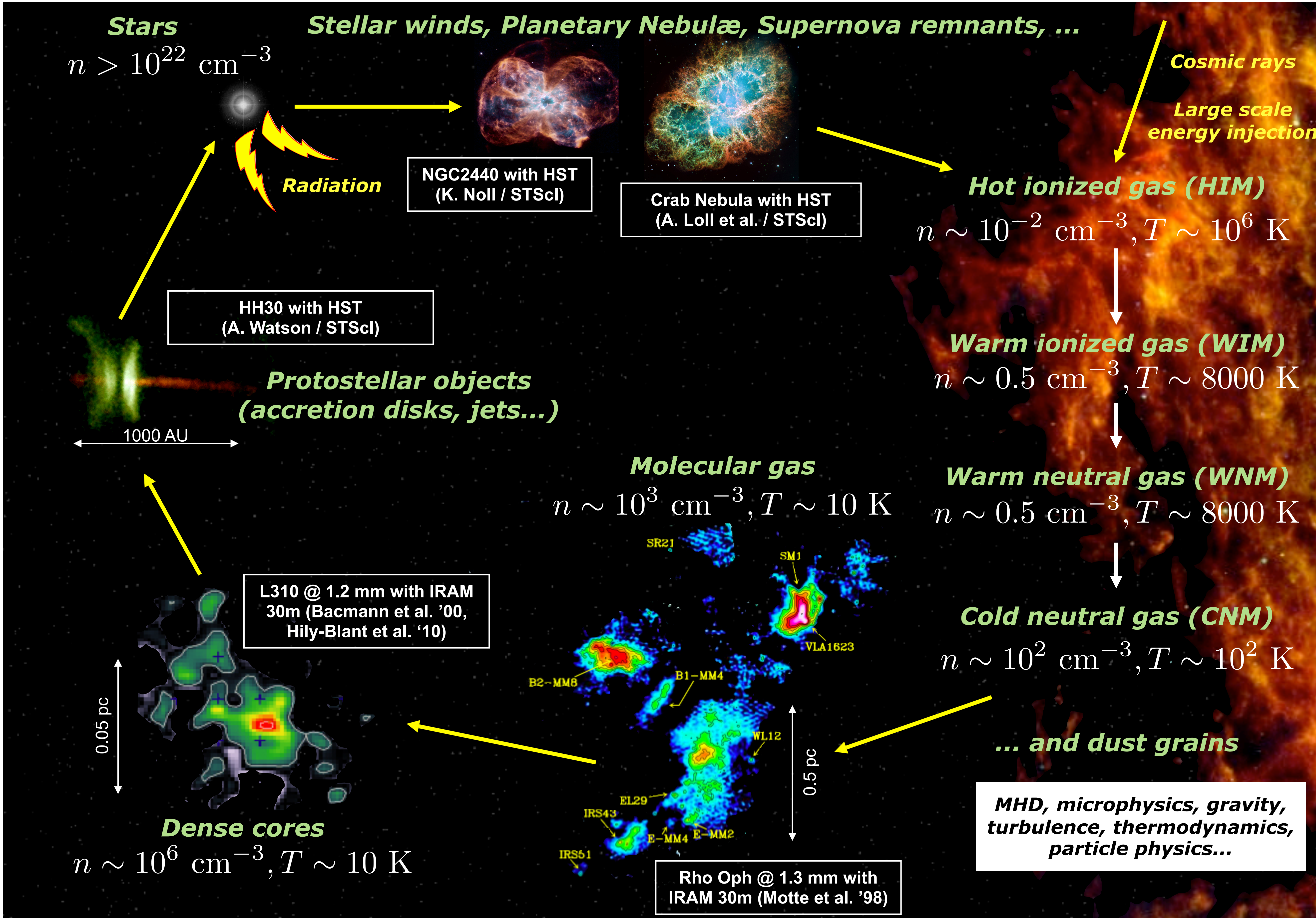
Post-processed chemistry on MHD simulations

- Application of the Meudon PDR code on lines of sight through MHD simulation cubes
- Evidence for "dark" molecular gas, not seen in CO
- Further ideas beyond the 1D PDR code

Simulated ALMA observations with GILDAS

- Simulated observations of large-scale MHD flows
- Simulated observations of collapsing cores
- Interpretation of observations

Star formation and the cycle of interstellar matter



The project's goals

Leading scientific questions

- What regulates star formation in galaxies ?
- What determines the stellar initial mass function (IMF) ?
- What governs the structure of molecular clouds ?
- How is energy injected ?
- Are clouds rather supported by the magnetic field or by turbulence ?
- How does gravitational collapse proceed ?

The STARFORMAT projects aims to give clues towards solving these by :

- *Putting together many cutting edge numerical simulations of the formation of molecular clouds, prestellar dense cores and circumstellar protoplanetary disks*

- *Spearheading the VO-Theory group to make these simulations available to the entire astrophysical community, through a web interface*

- *Thus providing observers a well-documented database of models useful for the preparation and interpretation of future observations (e.g. with ALMA)*

The STARFORMAT project

One of 5 projects funded by the European ASTRONET initiative (First joint call for proposals "Common Tools for Future Large submm Facilities" - september 2008)

ASTRONET
www.astronet-eu.org

French German collaboration involving 4 teams

Paris Observatory/LERMA-ENS:

Patrick Hennebelle (French PI)

Pierre Lesaffre, Edith Falgarone, Francois Levrier, Marc Joos, Benjamin Ooghe, Jean-Francois Rabasse, Nicolas Moreau

Paris Observatory/LUTH:

Franck Le Petit, Jacques Le Bourlot, Cecilia Pinto

University of Heidelberg and MPIA:

Ralf Klessen (German PI)

Robi Banerjee, Simon Glover, Cornelis Dullemond, Paul Clark, Milica Milosavjevic, Christoph Federrath, Benoît Commercon

University of Hamburg:

Peter Hauschildt

Financial overview

2 postdoctoral positions for 2 years

1 Heidelberg : Coupling between AMR and radiative transfer codes

1 Meudon/LUTH : Development of 3D PDR code

2 PhD positions

1 Heidelberg : Perform large scale MHD simulations

1 Lerma-ENS : Study MHD collapse and fragmentation

1 sofware engineer for 2 years

Lerma-ENS / Meudon: Build the database

Four realms of expertise - Project deliverables

Compressible MHD simulations

Perform large scale MHD and self-gravitating simulations (10^9 cells) to study molecular cloud and dense core formation

Perform a series of smaller simulations extracted from the larger ones to study dense core collapse in great detail

Radiative transfer

Post-process the 3D simulations using simple chemistry and compute continuum and simplified line radiative transfer

Compute “on the fly” (i.e. coupled to MHD simulation) simplified radiative transfer and simple chemistry

Detailed chemistry

Extract profiles from the simulations and use 1D PDR code to make predictions on abundances and spectral lines

Develop a 3D PDR code

Database

Build a VO-compatible database of clumps and cores extracted from the simulations including statistics, full clumps details and radiative transfer maps

Link it to the Meudon-PDR code

Expertise and available codes

@ LERMA/ENS

MHD, out of equilibrium chemistry, observations of MC

RAMSES

@ LUTH

Detailed equilibrium chemistry, radiative transfer, database work

PDR code and database

@ University of Heidelberg / MPIA

MHD, out of equilibrium chemistry, radiative transfer

FLASH, GADGET, RADMC, RADMC-3D

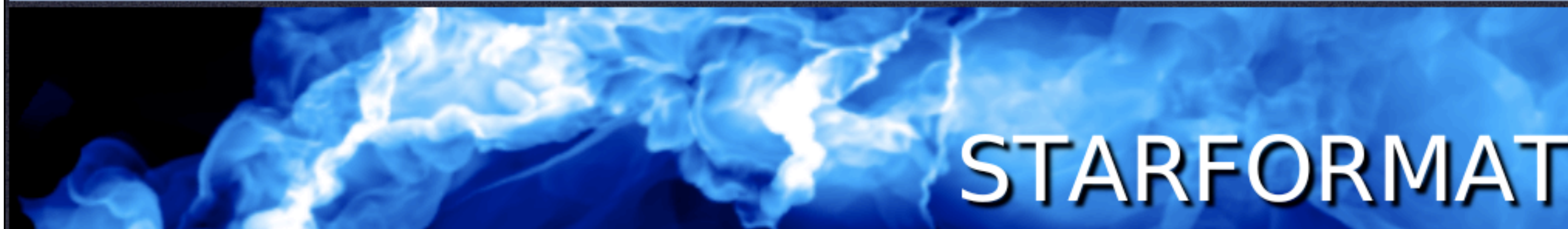
@ University of Hamburg

Radiative transfer

PHOENIX

The STARFORMAT web interface

SIMULATIONS DESCRIPTION



The StarFormat DataBase

The StarFormat database contains results of heavy numerical simulations computed in order to study the problem of star formation, essentially molecular cloud formation, evolution and collapse.

Understanding the dynamical evolution of the interstellar medium (ISM) and its relation to stellar birth is a key challenge in astronomy and astrophysics. The **STAR FORMAT** project aims at providing observers and theorists studying formation and evolution of molecular clouds, their morphological and kinematical characteristics, and the formation of stars in their interior with a set of theoretical tools and a database of models to aid in the analysis and interpretation of current and future observations.

The goal of this database is to give access to observers, or more generally to any scientist working on a related field, to the results of these numerical simulations, which could be useful to help prepare or analyze observations.

Available projects:

PROJECT	DESCRIPTION
Colliding flow simulations	This project aims at describing self-consistently the formation of molecular clouds starting from the very diffuse atomic interstellar medium.
Molecular cloud evolution with decaying turbulence	This project aims at describing the evolution of a turbulent molecular cloud in which the turbulence is decaying.
Solenoidal vs. Compressive Turbulence Forcing	This project investigates the influence of different forcing (i.e., kinetic energy injection) on turbulent flows in the interstellar medium.
Chemistry simulations	blablabla
Dark Energy Universe Virtual Observatory (DEUVO)	This project aims at investigating the imprints of dark energy on cosmic structure formation through very high resolution cosmological simulations

top of page

Organisation of the database

PROJECT:
Gather related numerical experiments
(Molecular cloud formation, core collapse,...)

PROTOCOL:
A single binary file : One code version, one type of boundary conditions and one type of initial conditions

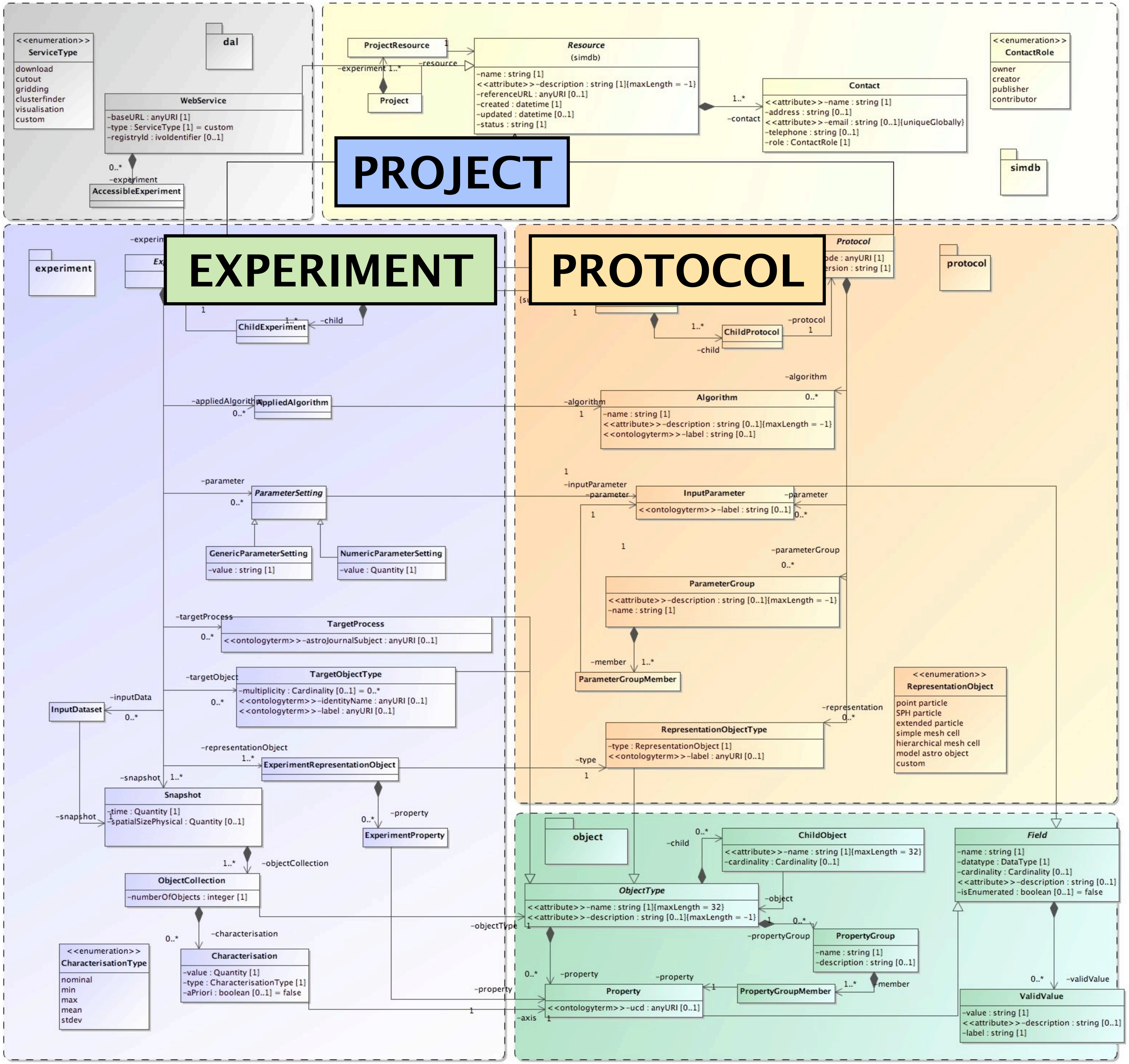
EXPERIMENT:
One choice of parameter values (boundary and initial conditions...)

SNAPSHOT:
Data for one timestep of the said numerical experiment

SUB-EXPERIMENT:
Calculations performed using the shapshot data :

- Clump extraction
- Line-of-sight extraction
- Post-processing steps (radiative transfer, chemistry, ...)
- ...

Data Model, or "Why we need software engineers"



© Scott Adams, Inc./Dist. by UFS, Inc.

Overview of the talk

The project

- Scientific context and questions
- Overview of the project
- Structure of the database

An example simulation : converging flows

- Accessing simulation results
- Statistics of "clumps" and comparison with observational data
- On-the-fly clump extraction
- Post-processed radiative transfer with RADMC-3D
- The other simulations in the database

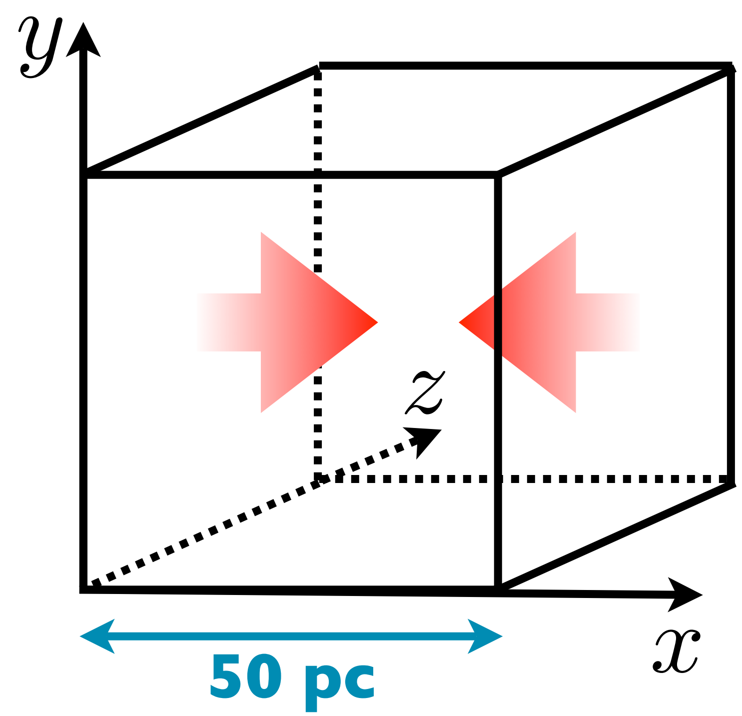
Post-processed chemistry on MHD simulations

- Application of the Meudon PDR code on lines of sight through MHD simulation cubes
- Evidence for "dark" molecular gas, not seen in CO
- Further ideas beyond the 1D PDR code

Simulated ALMA observations with GILDAS

- Simulated observations of large-scale MHD flows
- Simulated observations of collapsing cores
- Interpretation of observations

An example simulation from the database

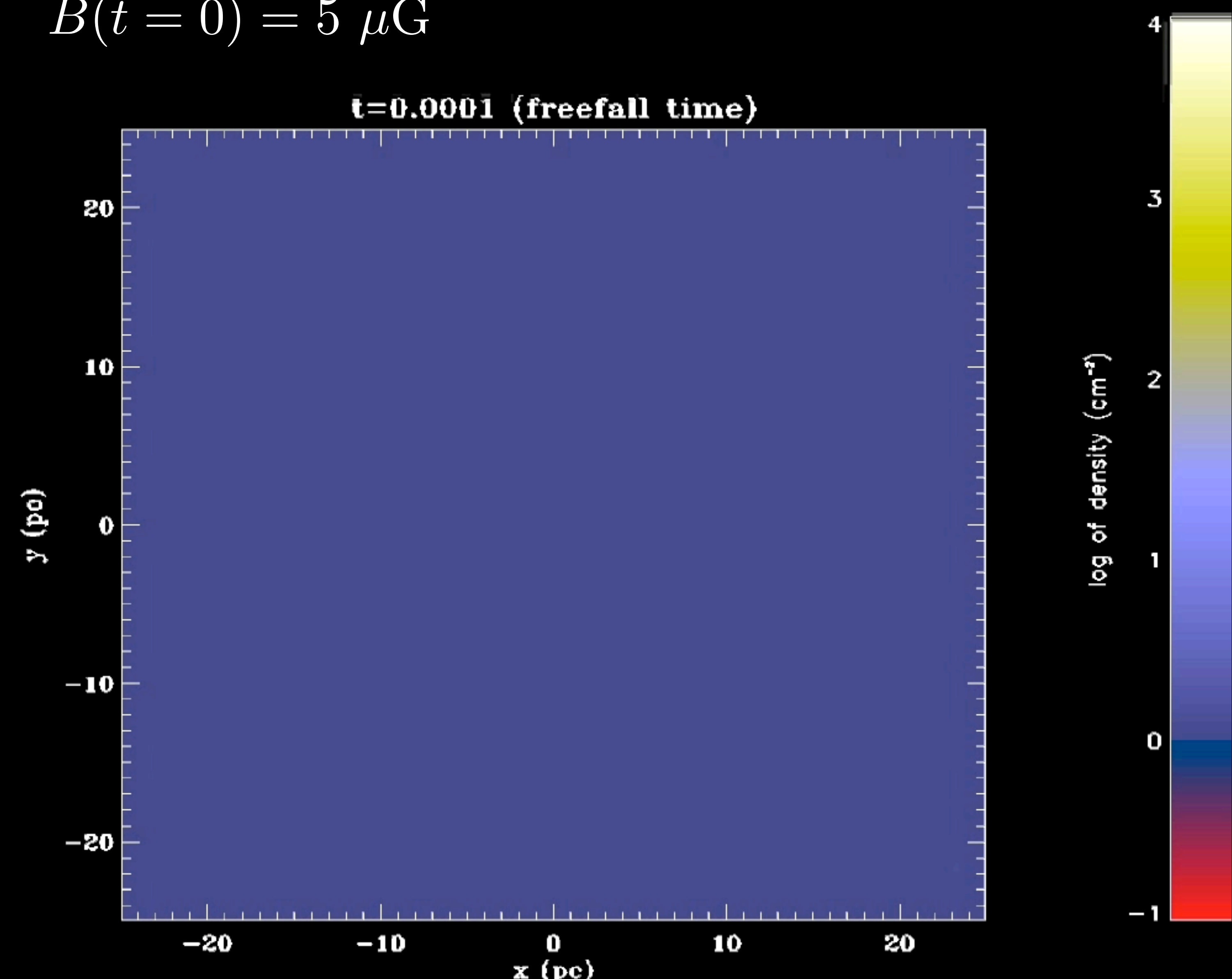


- RAMSES code (Teysier 2002, Fromang et al. 2006)
- Adaptive Mesh Refinement with up to 14 levels
- Periodic boundary conditions
- Includes magnetic field, atomic cooling and gravity
- Covers scales 0.05 pc - 50 pc
- ~30,000 CPU hours / 10 to 100 GB data sets

Converging flows of WNM

$n = 1\ \mathrm{cm}^{-3}$ $T = 10^4\ \mathrm{K}$ $v = 20\ \mathrm{km.s}^{-1}$

$B(t=0) = 5\ \mu\mathrm{G}$



Hennebelle et al. (2008)

What's in a sim ? (I)

PROJECT : Colliding flow simulations

Contacts : Patrick Hennebelle, Edouard Audit

Scientific case for the simulations :
This project aims at describing self-consistently the formation of molecular clouds starting from the very diffuse atomic interstellar medium.

Description of the simulations : A flow of warm neutral medium is arbitrarily imposed. Under the influence of cooling and ram pressure first, and then also of gravity, the gas undergoes a series of contractions until gravity takes over and triggers the formation of dense cores.

References : Hennebelle et al. L43 A&A 486, 2008

PROTOCOL (**PROTOCOL** **PROTOCOL**)

What's in a sim ? (II)

PROTOCOL : Converging flows

Contacts : Patrick Hennebelle, Edouard Audit, VO-Paris Data Centre

Code reference and description : RAMSES-MHD code (Teyssier 2002, A&A, 385, 337, Fromang et al. 2006, A&A, 457, 371). This is a mesh refinement code, implying that spatial resolution can be increased locally by adding new cells. It uses the Godunov method and constraint transport method to maintain the divergence of the magnetic field equal to zero.

Description of the simulation : Starting the simulation with only static Warm Neutral Medium, a converging flow is imposed from two sides. The converging flows have a velocity equal to a few times the sound speed of ambient WNM. Fluctuations are imposed on top of that mean velocity field. The magnetic field is initially uniform. The simulations includes atomic cooling and gravity. After a few million years, dense cores form and eventually collapse.

Definition of the simulation parameters :
Box size, resolution levels, incoming velocity, fluctuation level, initial magnetic field, initial density, initial temperature

EXPERIMENT	EXPERIMENT	EXPERIMENT	EXPERIMENT
MHD simulation (1024^3) "Fiducial run"	MHD simulation (1024^3) with lower forcing	Hydro simulation (1024^3)	High-resolution MHD simulation (4096^3)

What's in a sim ? (III)

EXPERIMENT : Fiducial run

Description of the run :

This run considered as «fiducial» has an effective numerical resolution equal to 1024^3 grid cells implying that the size of the smallest cell is about 0.05 pc. The magnetic field in the run and the velocity of the incoming flow are about 5 microGauss initially (but get amplified in the dense regions) and 18 $km.s^{-1}$ (about twice the sound speed of the warm neutral phase).

Applied physics :

Magneto Hydro Dynamics

Magneto-hydrodynamics is treated in this simulation. This implies that the gas is subject to Lorentz forces while the evolution of the magnetic field is dictated by the induction equation.

Gravity

Self-gravity is treated in this simulation. This implies that at each timestep, the Poisson equation is solved to obtain the gravitational potential and the gravitational forces.

Atomic cooling

Atomic cooling is included as described in Wolfire et al. 1995, ApJ, 453, 673 following the implementation described in Audit & Hennebelle, 2005, A&A, 433, 1.

Heating

Photo electric heating on dust grains and PaH is implemented as described in Wolfire et al. 1995, ApJ, 453, 673 following the implementation described in Audit & Hennebelle, 2005, A&A, 433, 1.

Values for the parameters defined in the PROTOCOL :

Box size	50 pc
Lowest resolution	0.39
Highest resolution	0.04
Magnetic Field - X Boundary	1 x5 microGauss
Incoming flow modulation	1
Initial density within the box	1 cm^{-3}
Initial temperature within the box	8000 K
Incoming flow velocity	17.79 km/s

SNAPSHOT

SNAPSHOT

SNAPSHOT

SNAPSHOT

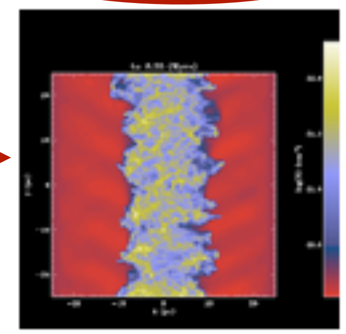
SNAPSHOT

What's in a sim ? (IV)

SNAPSHOT : Fiducial run at t=8.55 Myrs

t = 8.55 MYRS

Column density along the z axis →



EXTRACT AND DOWNLOAD SNAPSHOT DATA

Snapshot statistics for cells above a threshold in density or column density →

STATISTICS ON ALL CELLS WITH

Density ≥ 0

Mean Magnetic Intensity	7.12 microGauss
Mean Density	6.17 cm^{-3}
Total Mass	2.622×10^4 solar mass
Mean Pressure	1.837×10^{-12} erg.cm^{-3}
Mean Temperature	1.704×10^3 K

What kind of values do you want to extract?

- a projection of column density
- a slice of density
- a slice of pressure
- a slice of velocity
- a slice of magnetic field

along which axis?

- X
- Y
- Z

Extraction size: 50,00 pc (50,00 pc for the whole simulation)

Centered on: X 25,00 (pc) Y 25,00 (pc) Z 25,00 (pc)

Precision L_{max}: 8 corresponding to a resolution of 0.195 pc/cell
(maximum L_{max} allowed for this size of extraction: 8)

E-mail address (to receive a link to download the results):

Extract Reset Cancel

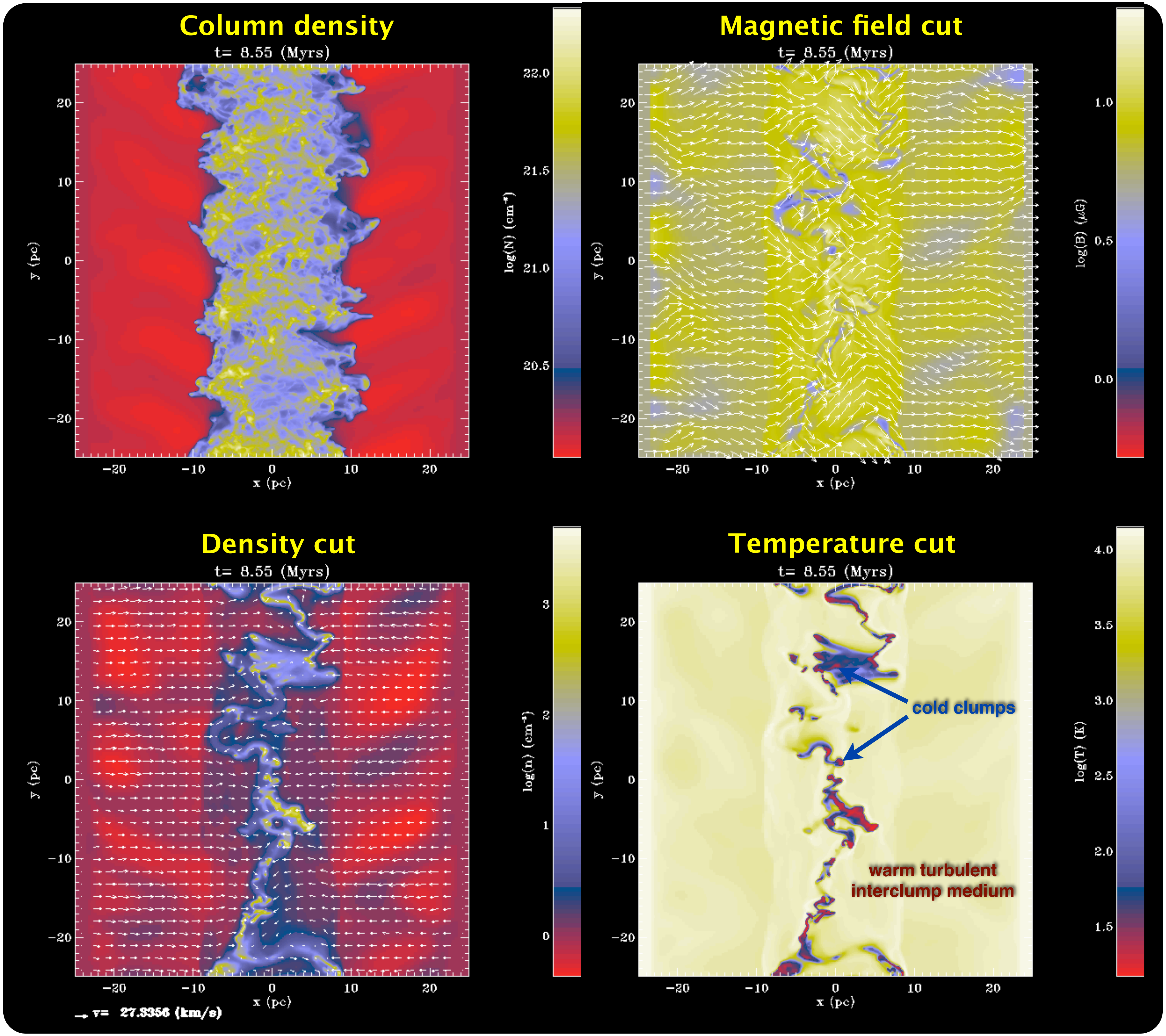
PROPERTY PLOTS

- Column Density in XY
- Column Density in XZ
- Column Density in YZ
- Density cut in XY
- Density cut in XZ
- Density cut in YZ
- Magnetic Intensity in XY
- Magnetic Intensity in XZ
- Magnetic Intensity in YZ
- Magnetic Intensity Variance vs. Density
- Magnetic Intensity vs. Density
- Mass vs. Column Density
- Mass vs. Density
- Pressure cut in XY
- Temperature cut in XY
- Temperature Variance vs. Density
- Temperature vs. Density

Download ASCII data

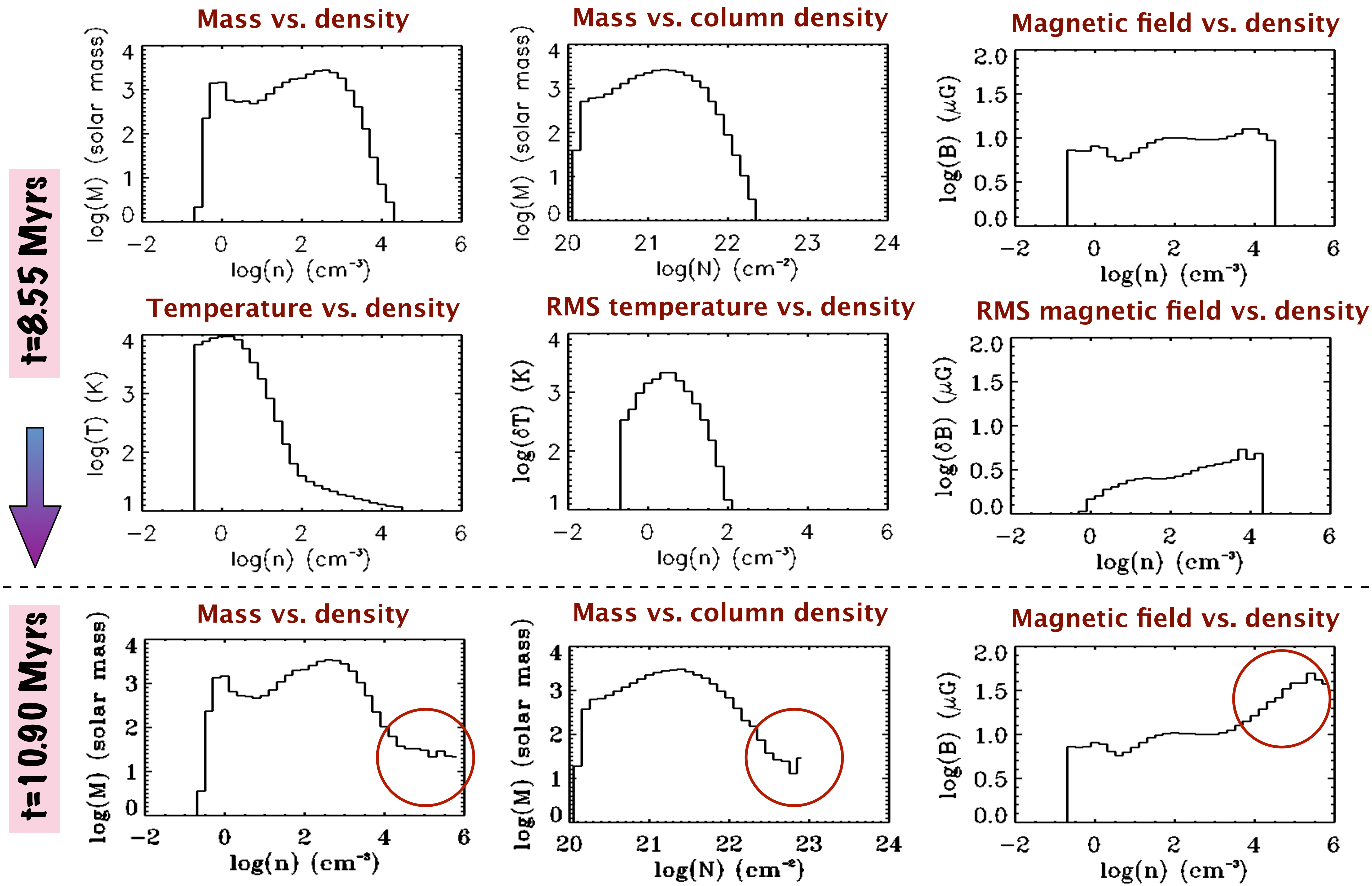
Download PNG plot or image

Snapshot properties



Snapshot properties

Also downloadable as ASCII data....



What's in a sim ? (V)

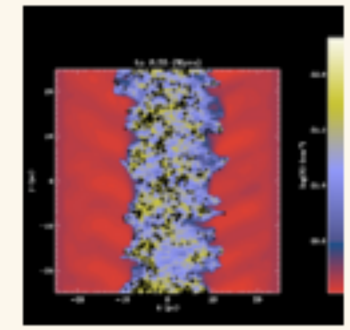
SUB-EXPERIMENT : Clump extraction at t=8.55 Myrs

Code : Clump extraction is performed in physical space. All cells whose density is larger than a specific threshold are selected. Then, applying a simple friend-of-friend algorithm, the spatially connected cells are identified and define a clump.

Parameters : Threshold in density (500 or 2500 cm^{-3})

CLUMPS WITH DENSITY ≥ 2500 CM^{-3}

POSITIONS :

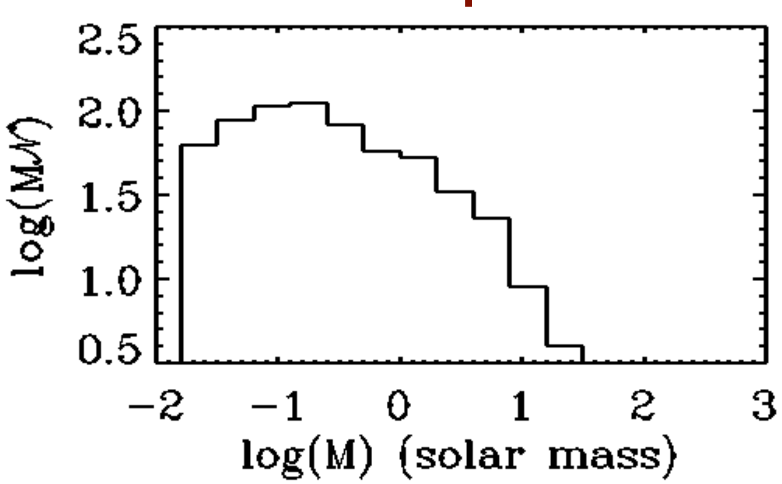


Download ASCII data → DOWNLOAD ALL PROPERTIES

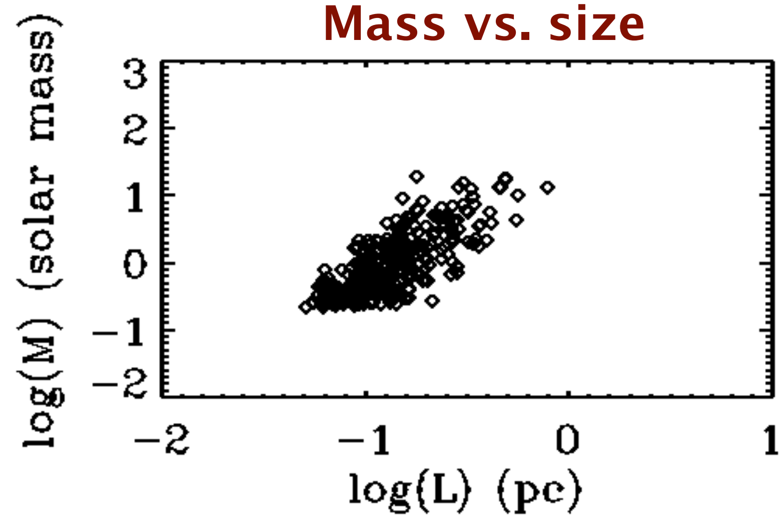
- Axis Ratio
- Beta vs. Mass
- Kinetic over Magnetic Energy vs. Mass
- Magnetic Energy vs. Kinetic Energy
- Magnetic Field (rms) vs. Mass
- Magnetic Field vs. Mass
- Mass Spectrum
- Mass to abs Flux vs. Mass
- Mass to Flux vs. Mass
- Mass vs. Size
- Specific Angular Momentum vs. Mass
- Specific Angular Momentum vs. Size
- Velocity Dispersion vs. Size

Download PNG plot

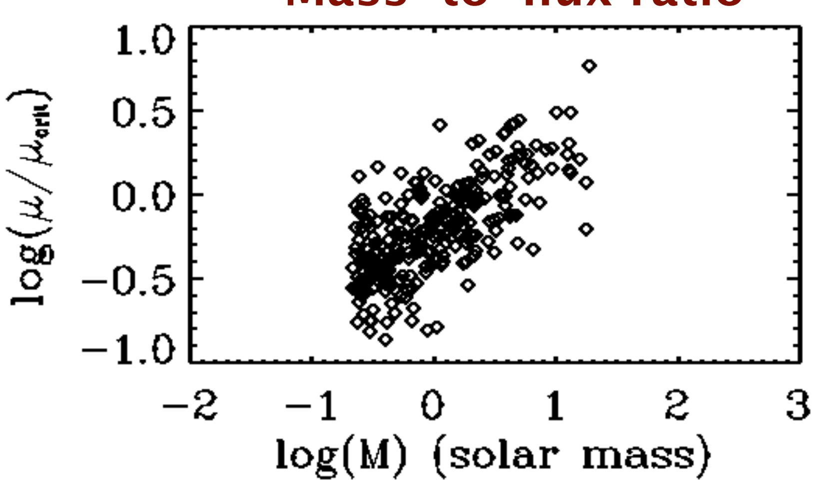
Mass spectrum



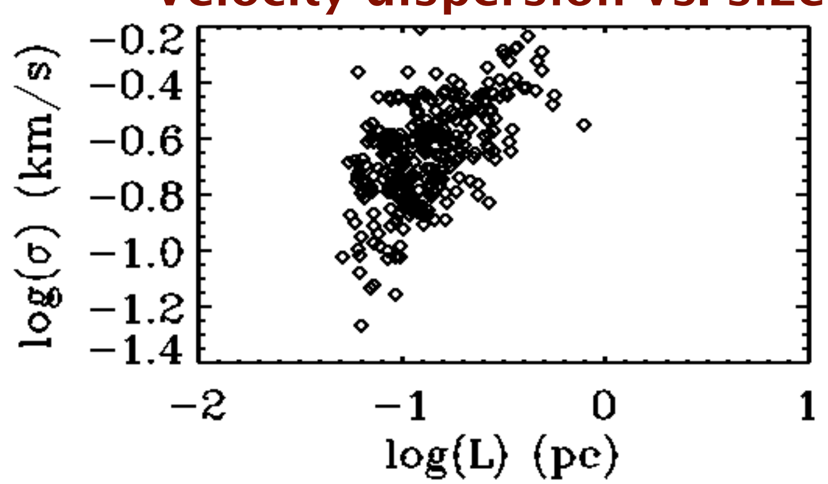
Mass vs. size



Mass-to-flux ratio

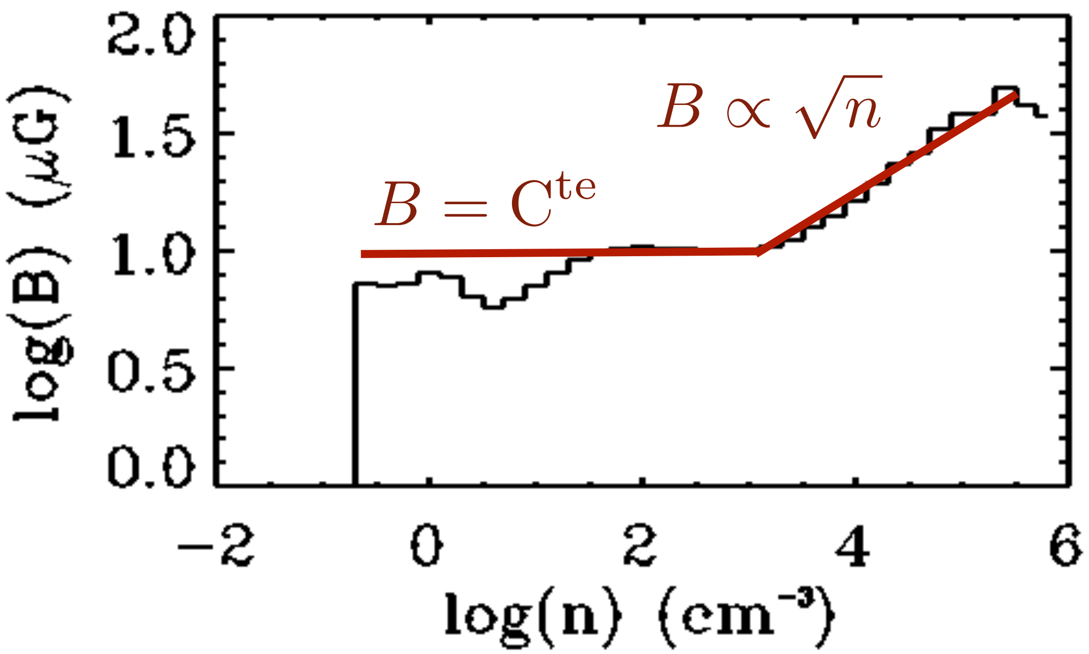


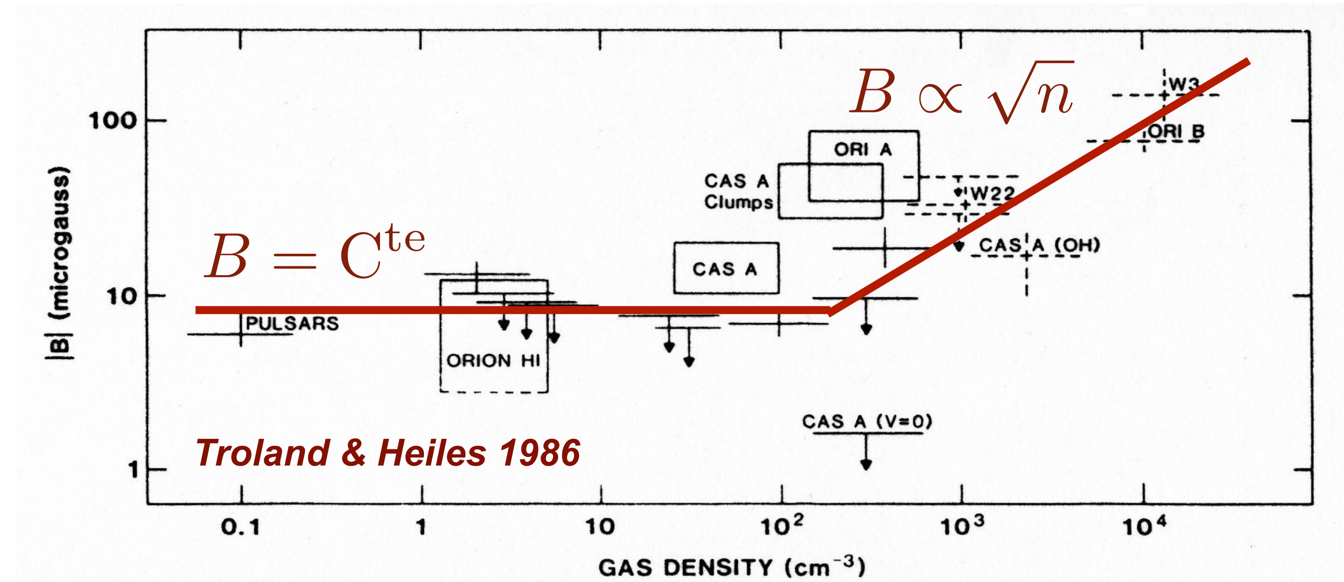
Velocity dispersion vs. size



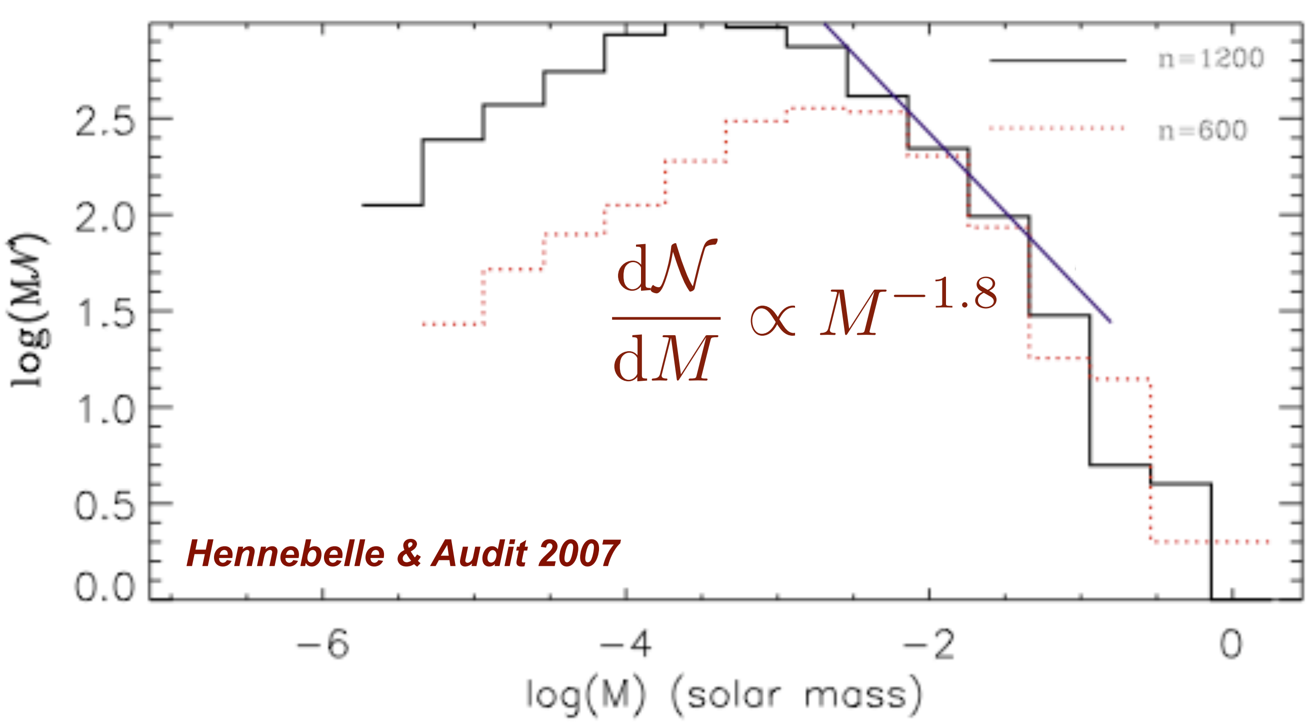
Comparison with observational data

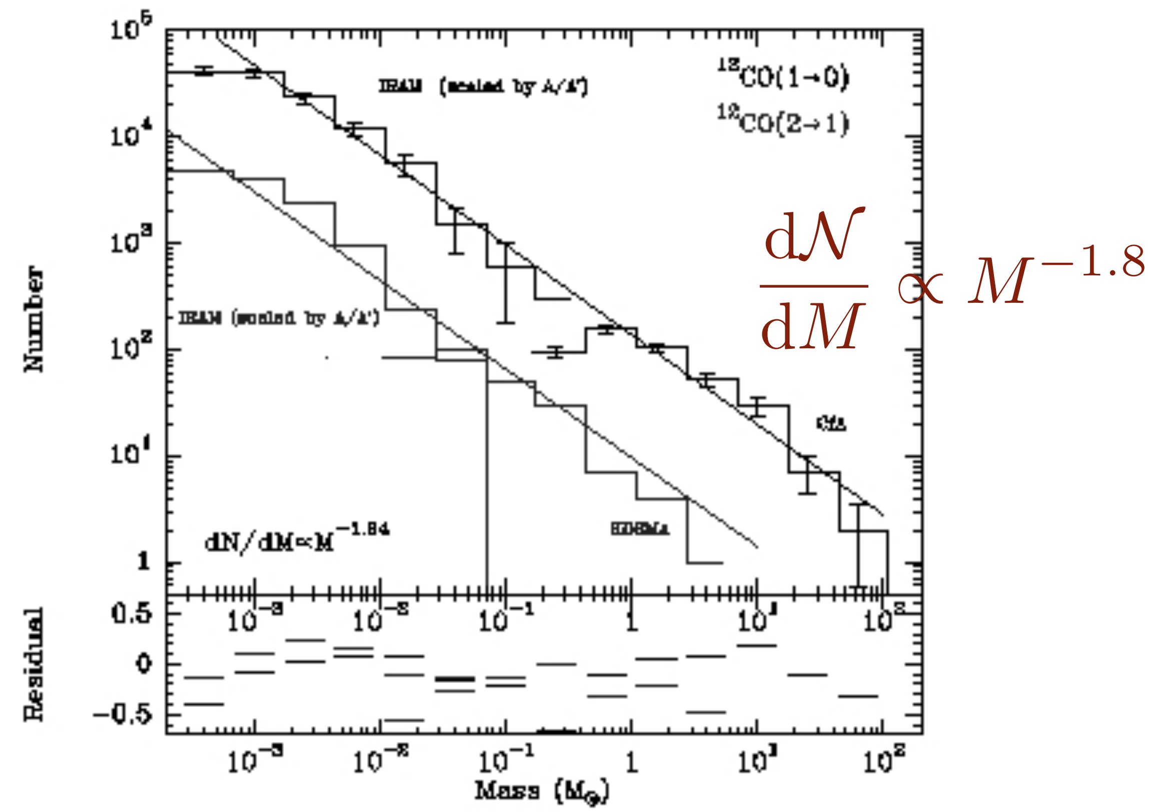
Magnetic field vs. density





Mass spectrum

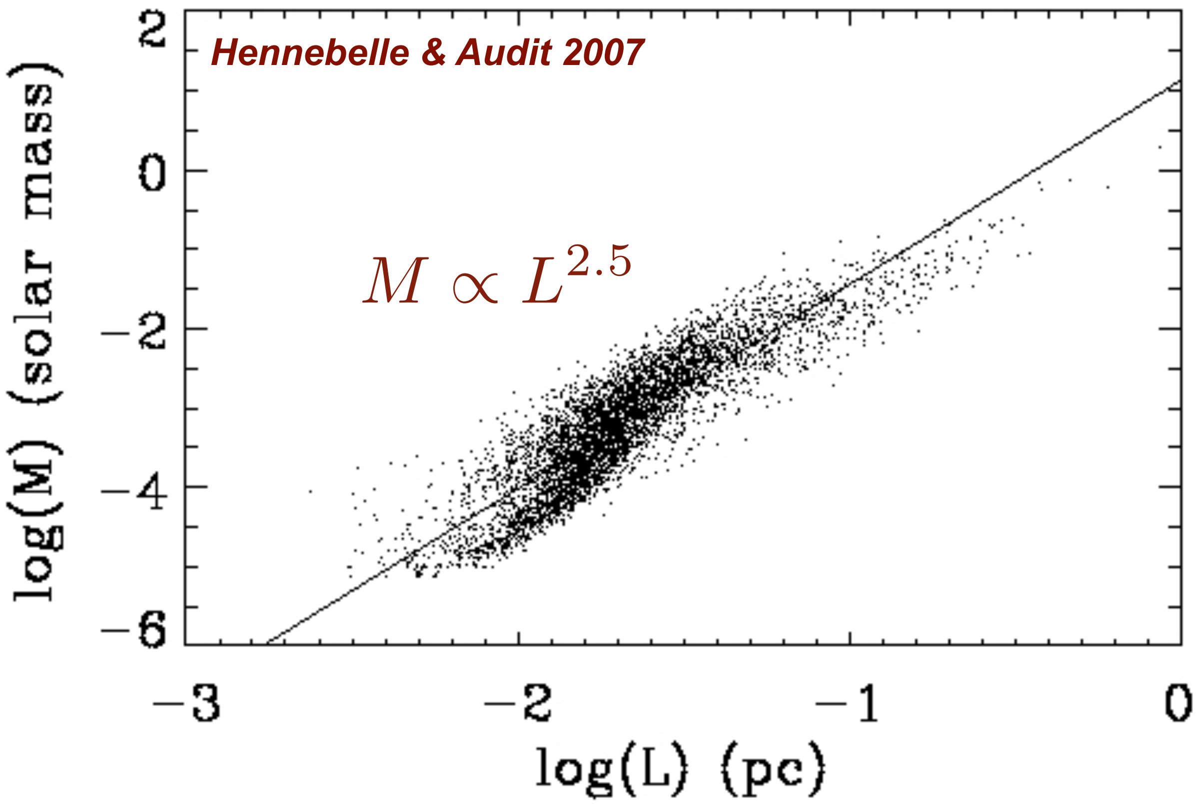


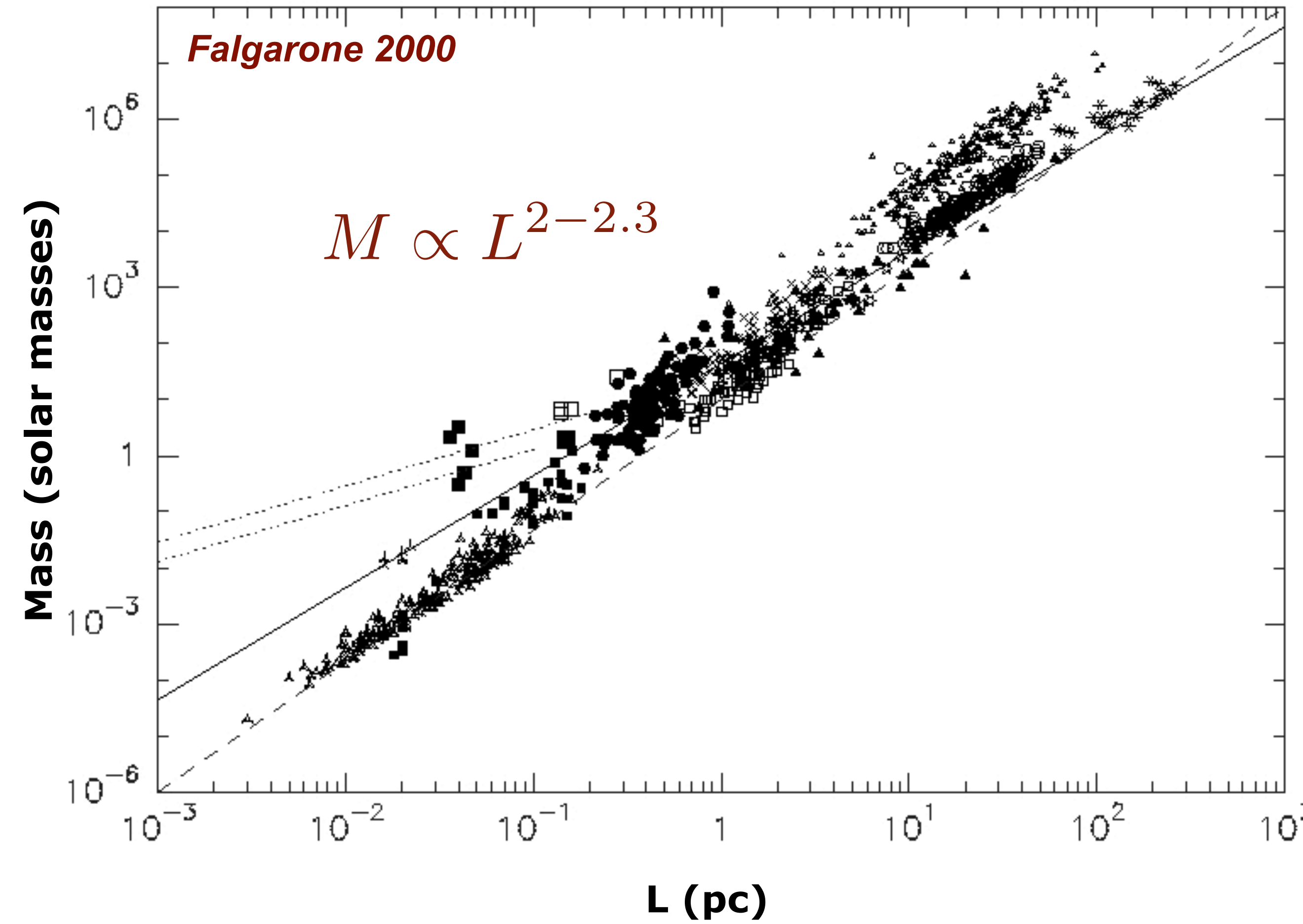


Heithausen et al. 1998

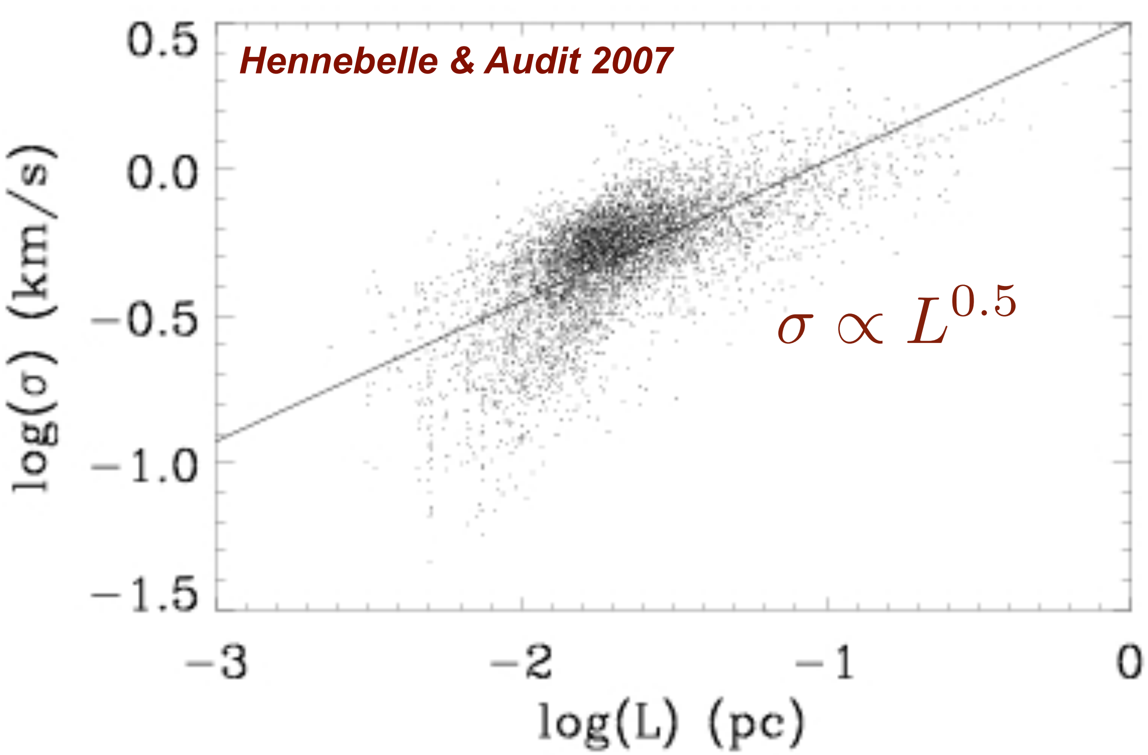
Comparison with observational data

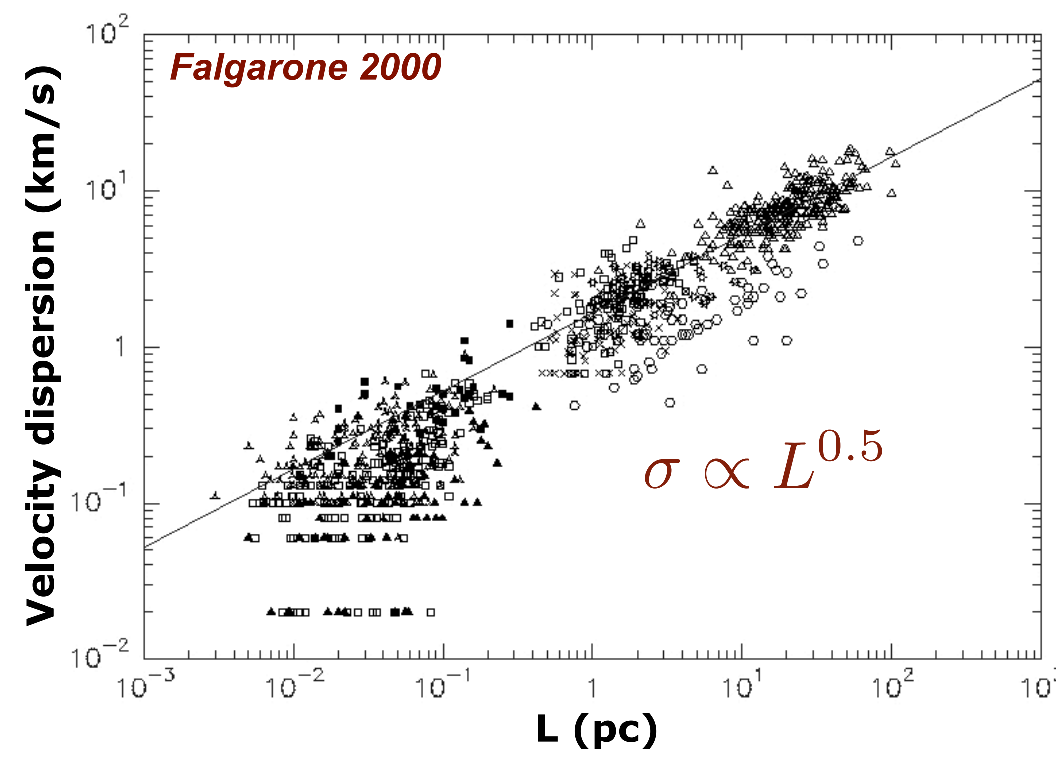
Mass vs. size





Velocity dispersion vs. size





Clump extraction (I)

Step 1 : Search one or several snapshots in one or several runs for clumps above a given threshold

Find Clumps within these simulations:

The clump extraction is performed in the physical space. All cells whose density is larger than a specific threshold are selected. Then, applying a simple friend of friend algorithm, the spatially connected cells are identified and define a clump.

Look for clumps with a minimum density of

○ 500 ◉ 2500 (cm^{-3})

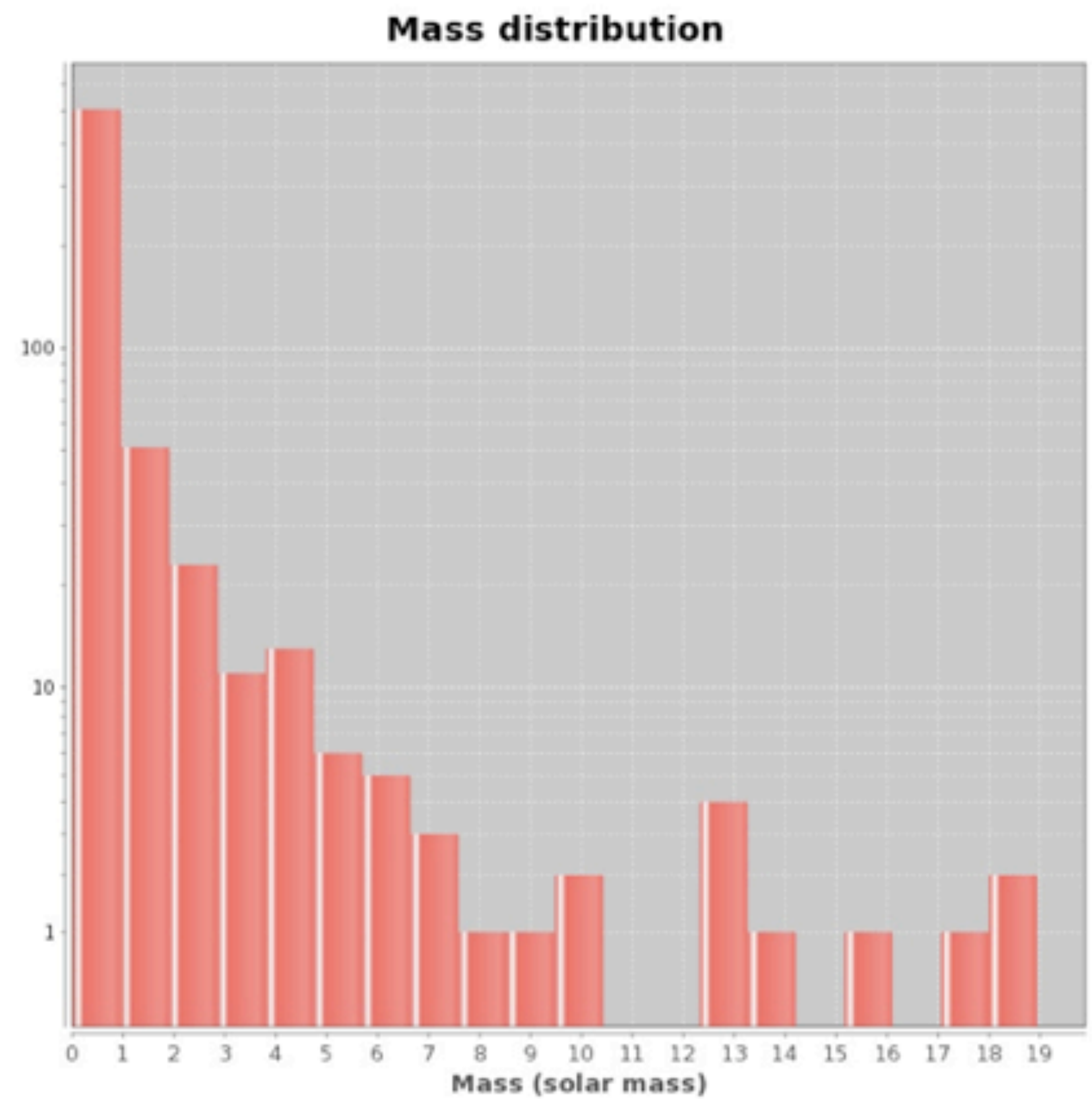
SEARCH THROUGH THE FOLLOWING SNAPSHOTS	
Hydrodynamical	8.38 Myrs ☐ 11.17 Myrs ☐
Fiducial	8.55 Myrs ☑ 10.90 Myrs ☐
Slower Flow	9.74 Myrs ☐ 16.29 Myrs ☐
High Resolution	16.74 Myrs ☐ 18.93 Myrs ☐

Select

631 clumps found. Browse them by property values:

PROPERTY	MINIMUM	MAXIMUM
Mass (solar mass)		
Density (cm^{-3})		
Structure size (pc)		

Search

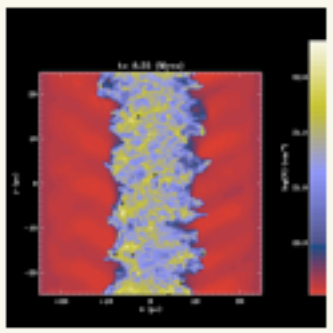


Outputs the distributions of masses, mean densities and size of matching clumps

Clump extraction (II)

Step 2 : Browse the results of step 1 by mass range, density range and size range

PROPERTY	MINIMUM	MAXIMUM
Mass (solar mass)	5	10
Density (cm^{-3})	3000	4000
Structure size (pc)	0.5	1

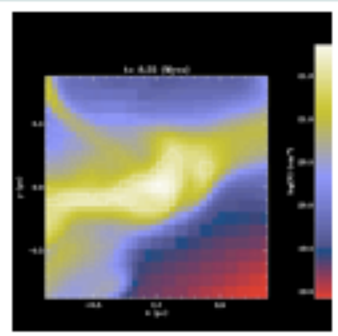


FIDUCIAL
t = 8.55 MYRS

8 CLUMPS FOUND
← SEE POSITIONS ON SNAPSHOT IMAGE

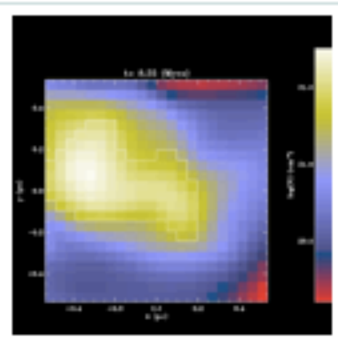
Mass : 5.08 solar mass
Density : 3.707E03 cm^{-3}
Structure size : 0.87 pc

View details

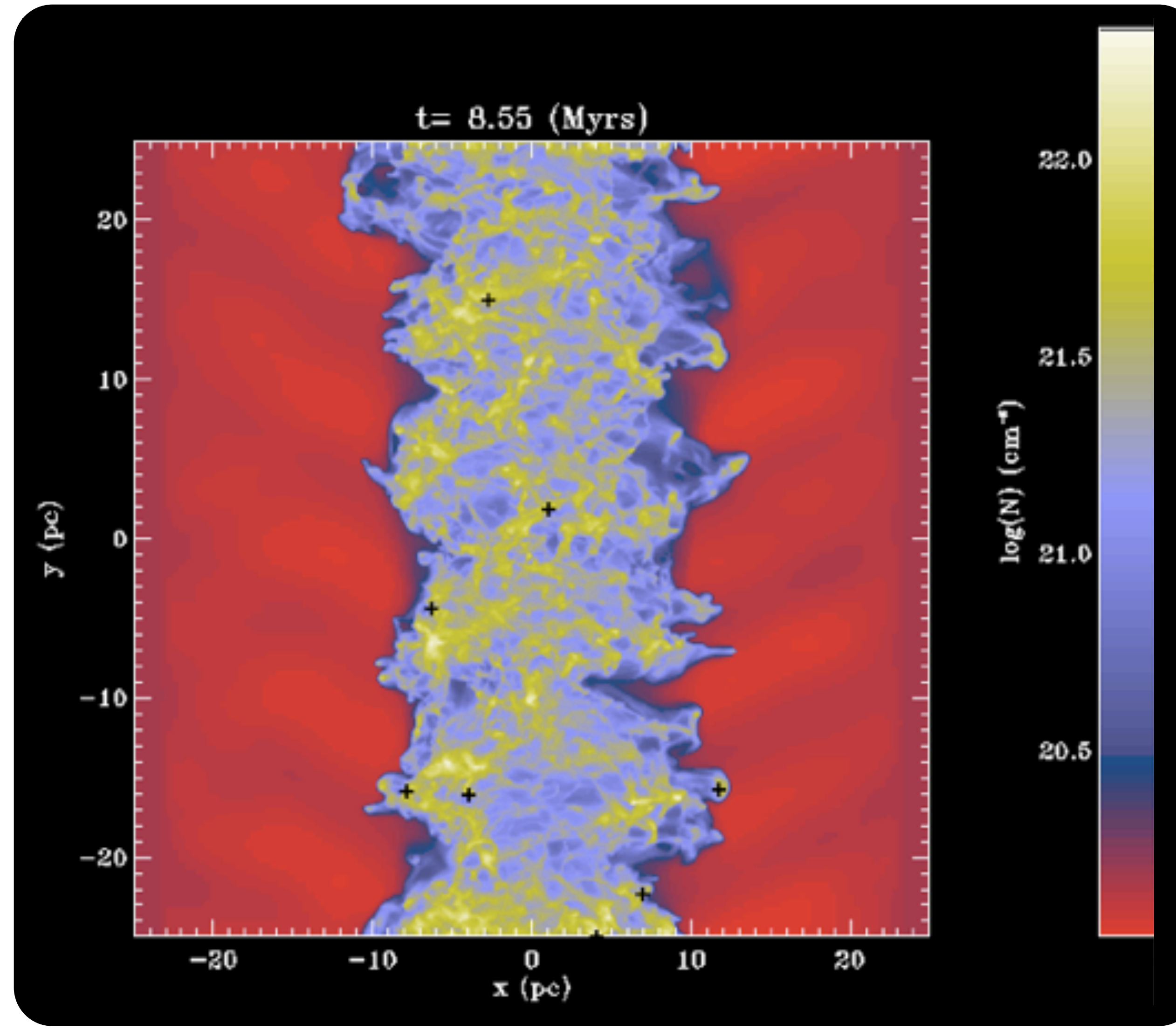


Mass : 5.97 solar mass
Density : 3.386E03 cm^{-3}
Structure size : 0.53 pc

View details



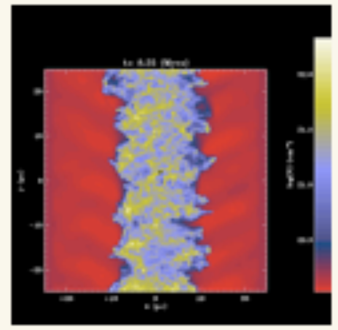
(...)



Clump extraction (III)

Step 3 : Select a clump from the list presented

SEE POSITION ON SNAPSHOT IMAGE →



CLUMP PROPERTIES

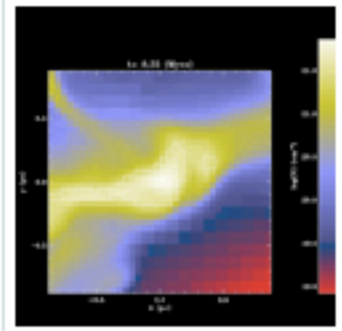
Angle	1.23 rad
Density	3.707×10^{3} cm^{-3}
Density Max	8.398×10^{3} cm^{-3}
Magnetic Field (rms value)	7.08 microGauss
Magnetic Field (X axis)	2.33 microGauss
Magnetic Field (Y axis)	-3.00 microGauss
Magnetic Field (Z axis)	-2.26 microGauss
Mass	5.08 solar mass
Mass to Flux	1.75
Number of cells	347
Position of the Clump Density peak (X)	26.02 pc
Position of the Clump Density peak (Y)	26.95 pc
Position of the Clump Density peak (Z)	28.07 pc
Position of the Clump Gravity Center (X)	25.92 pc
Position of the Clump Gravity Center (Y)	26.92 pc
Position of the Clump Gravity Center (Z)	28.06 pc
Pressure	7.931×10^{-12} $erg.cm^{-3}$
Structure size	0.87 pc
Velocity Dispersion	0.22 $cm.s^{-1}$
Velocity (X axis)	-2.997×10^{4} $cm.s^{-1}$
Velocity (Y axis)	1.908×10^{4} $cm.s^{-1}$
Velocity (Z axis)	2.130×10^{3} $cm.s^{-1}$

BACK TO THIS CLUMP IN SEARCH RESULTS

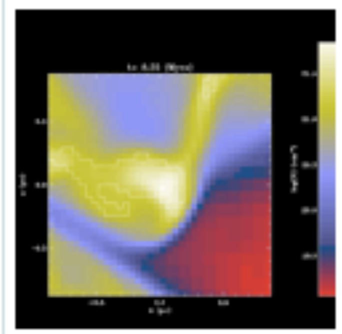
EXTRACT AND DOWNLOAD CLUMP DATA

DOWNLOAD ARCHIVE WITH ALL VALUES AND IMAGES

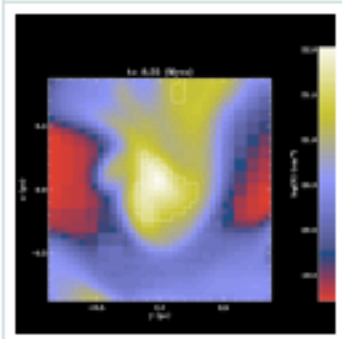
CLUMP IMAGES



Column Density in XY



Column Density in XZ

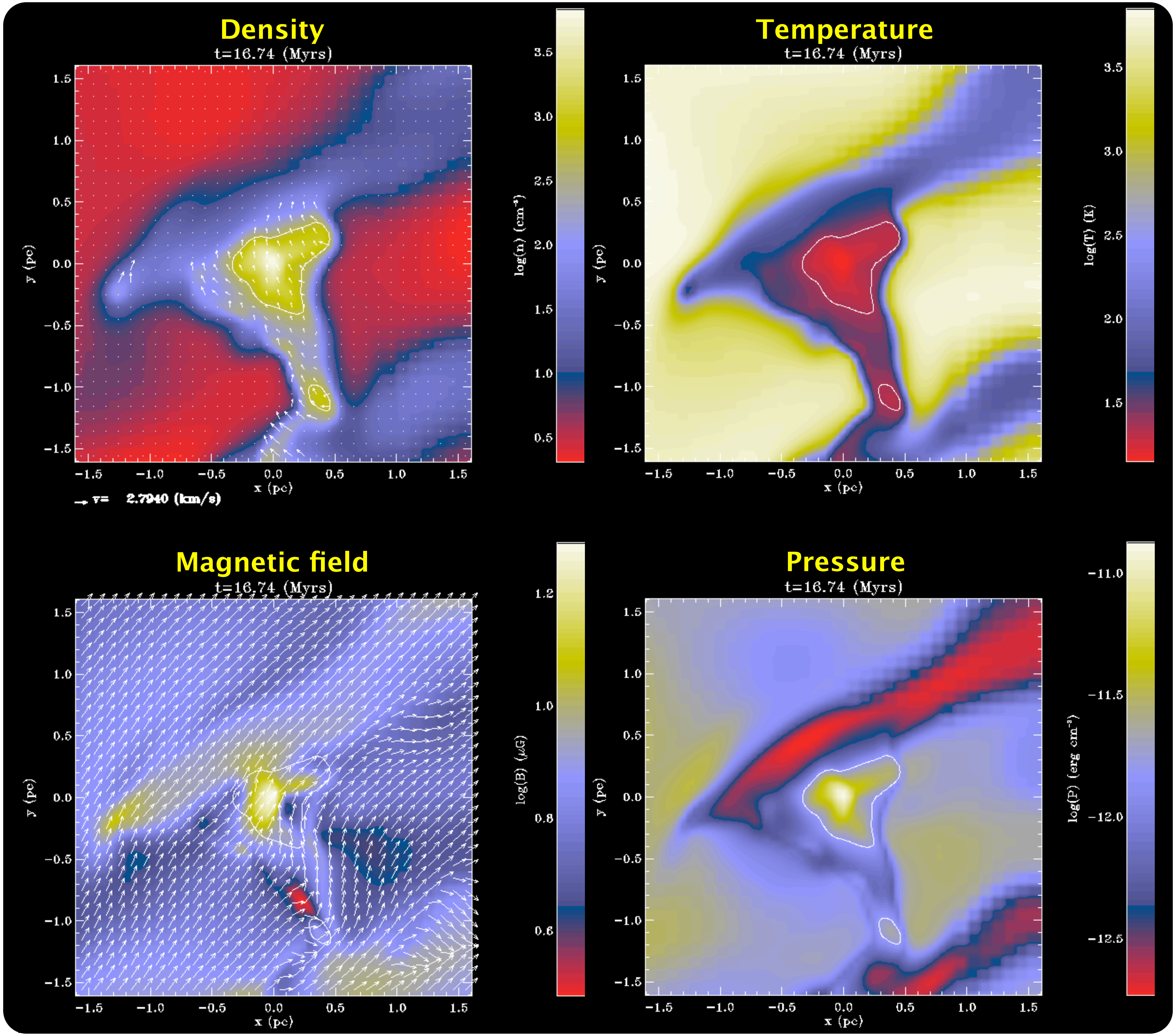


Column Density in YZ

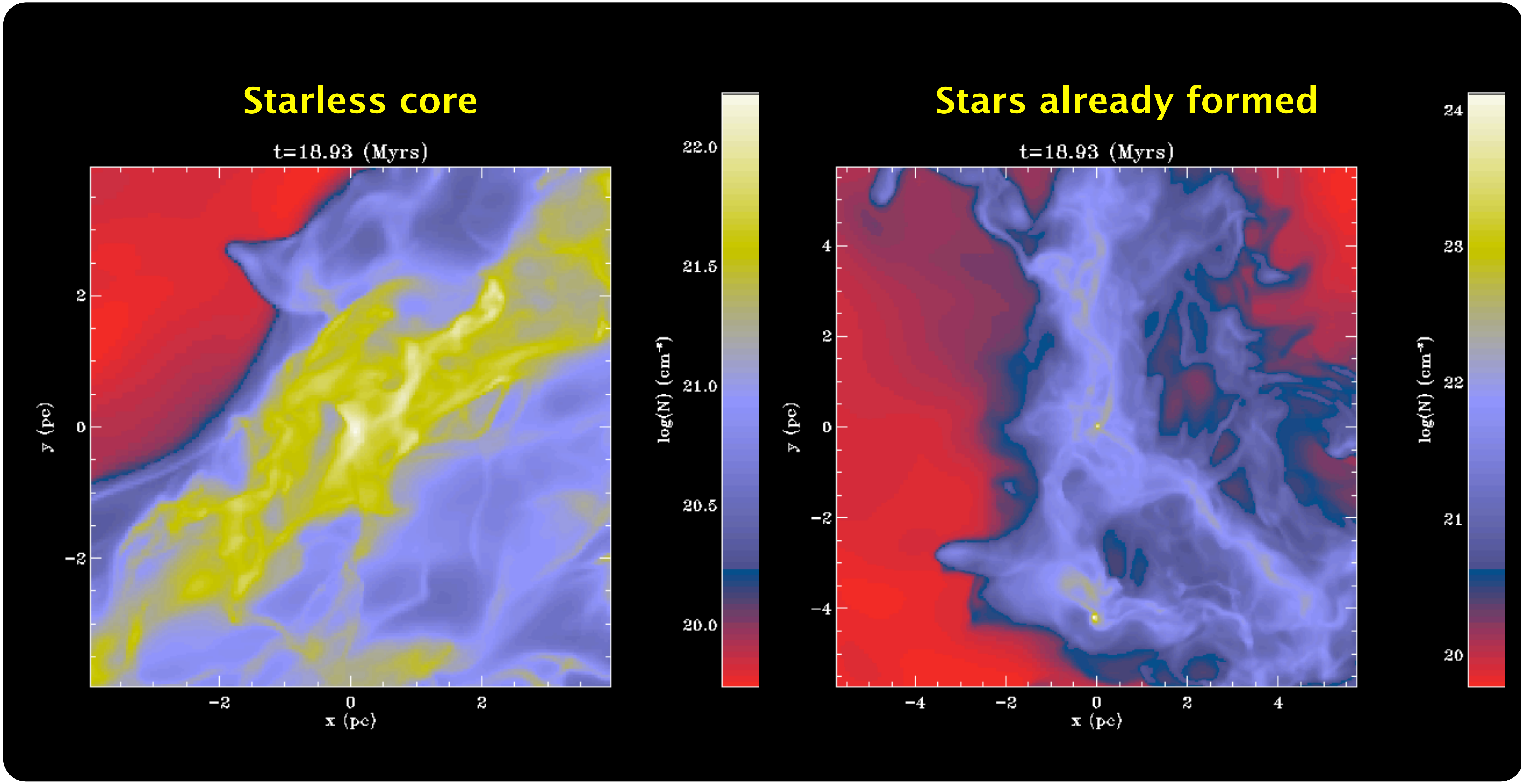
Download PNG image

Also density, magnetic field intensity, temperature and pressure cuts...

Example of a forming dense core



It takes all kinds of clumps...



Clump extraction (IV)

BACK TO THIS CLUMP IN SEARCH RESULTS

EXTRACT AND DOWNLOAD CLUMP DATA

Extract a subset of clump data from the simulation

or Calculate radiation transfer on this clump thanks to RADMC-3D

What kind of values do you want to extract?

- ○ a projection of column density
- ◉ a cube of density
- ○ a cube of pressure
- ○ a cube of velocity
- ○ a cube of magnetic field

Extraction box size: [1,76] pc (50,00 pc for the whole simulation)

Centered on: X [26,025] (pc) Y [26,953] (pc) Z [28,076] (pc)

Precision L_{max}: [10] corresponding to a resolution of 0.048 pc/cell
(maximum L_{max} allowed for this size of extraction: 12)

E-mail address (to receive a link to download the results): [levrier@lra.ens.fr]

[Extract] [Reset] [Cancel]

Extraction started

Data extraction is currently being processed.
You will receive an e-mail at your address levrier@lra.ens.fr with a link to download the file in a few minutes.

You can now close this window or click here to perform another extraction.

StarFormat clump extraction

amr2cube-r2 -inp /SfsDB/raw/data/FORM_MC/THY3D_grav_mag_bcl/output_00026 -out SFExtract.tmp -xmi 0.5029 -xma 0.5380999999999999 -ymi 0.52146 -yma 0.5566599999999999 -zmi 0.5439200000000001 -zma 0.57912 -lma 10 -typ 1 -scl 1.0 -fil ascii
Experiment/snapshot: FORM_MC/THY3D_grav_mag_bcl/output_00026
Snapshot time: 8.550265 Myrs
Center position (pc): X=26.025; Y=26.953; Z=28.076
Extraction size: 1.76 pc
density (cm^-3)

i	j	k	value
0	0	0	0.64124954D+02
1	0	0	0.64124954D+02
2	0	0	0.67942116D+02
3	0	0	0.63388466D+02
4	0	0	0.54006287D+02
5	0	0	0.52991573D+02
6	0	0	0.50049461D+02
7	0	0	0.52863888D+02
8	0	0	0.66866089D+02
9	0	0	0.89408325D+02
10	0	0	0.10401249D+03
11	0	0	0.89820068D+02
12	0	0	0.45492512D+02
13	0	0	0.19445061D+02

(...)

FITS files expected in the near future

Post-processed radiative transfer with RADMC-3D

BACK TO THIS CLUMP IN SEARCH RESULTS

EXTRACT AND DOWNLOAD CLUMP DATA

Calculate radiation transfer on this clump thanks to RADMC-3D

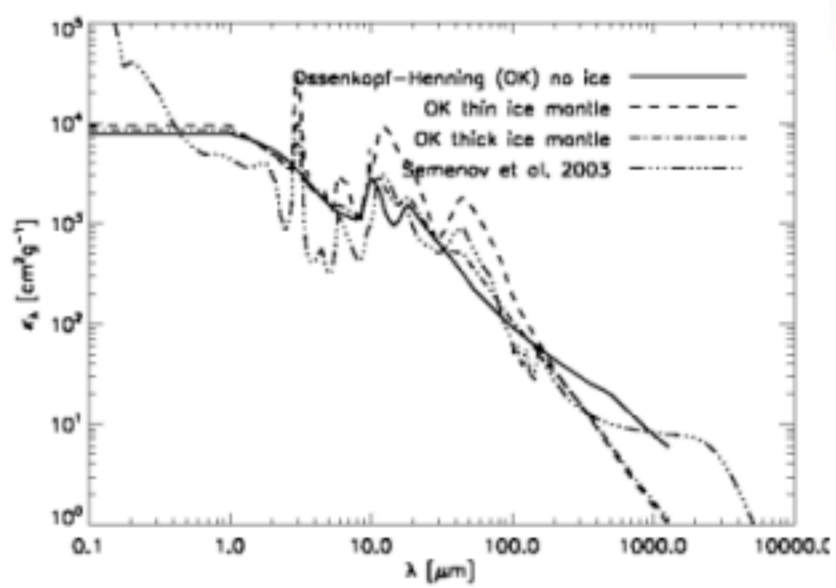
or Extract a subset of clump data from the simulation

What do you want to calculate?

- an image
- a SED

Which dust opacity model do you want to use?

- No ice
- Thin ice
- Thick ice
- Silicate
- Semenov



Clump box size: 1,76 pc (50,00 pc for the whole simulation)

Centered on: X 26,025 (pc) Y 26,953 (pc) Z 28,076 (pc)

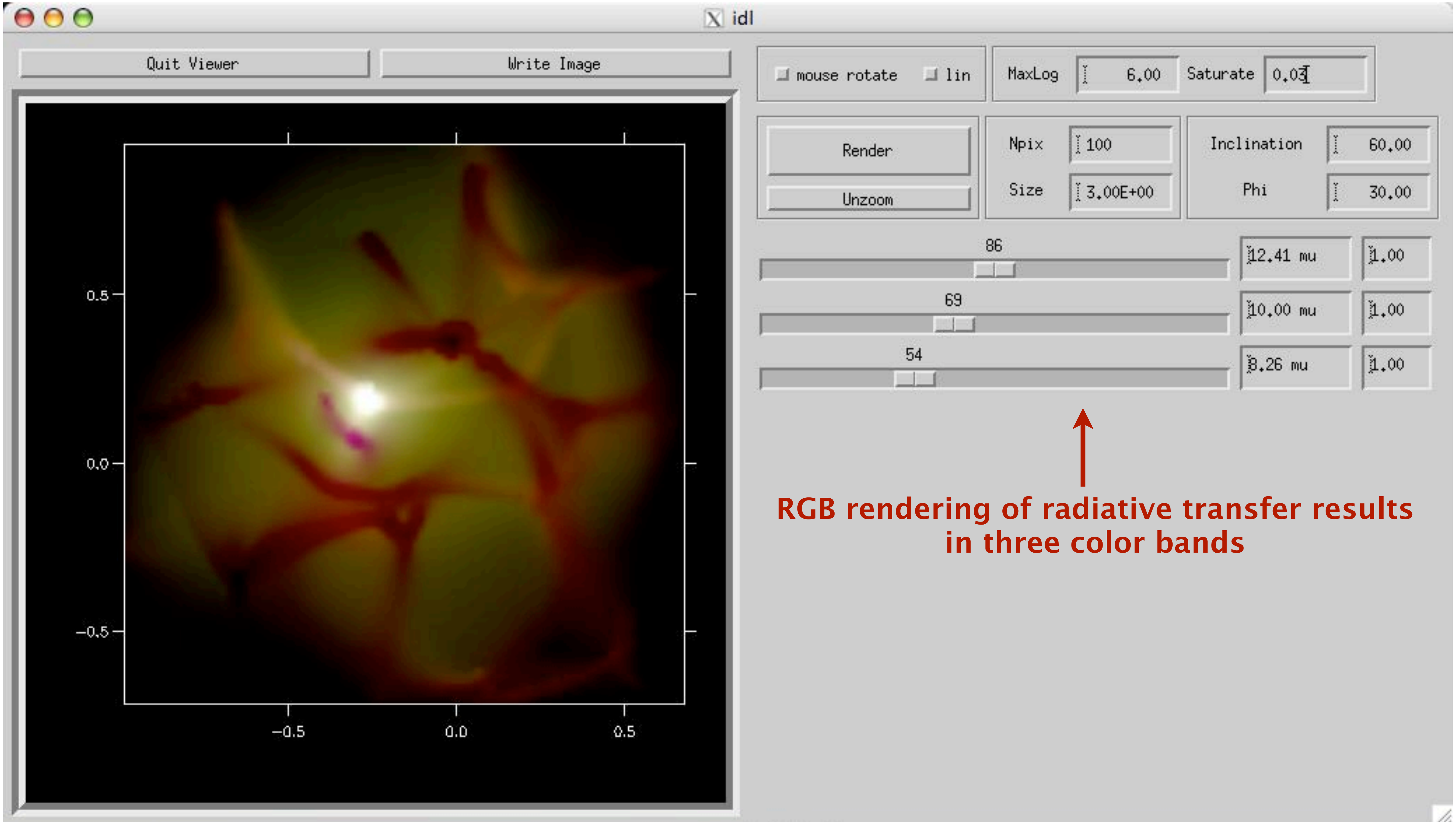
Precision L_{max}: 10 corresponding to a resolution of 0.048 pc/cell (maximum L_{max} allowed for this size of extraction: 12)

E-mail address (to receive a link to download the results):

Extract Reset Cancel

RADMC-3D

http://www.ita.uni-heidelberg.de/~dullemond/software/radmc-3d/



- Radiative transfer code using Monte-Carlo approach
- Works with Cartesian or spherical geometries, and compatible with AMR grids
- Interfaces with simulation codes FLASH, RAMSES, ZEUS
- Graphical User Interface in IDL for exploration of code results

Other simulations in the STARFORMAT database

PROJECT : Molecular cloud evolution in decaying turbulence

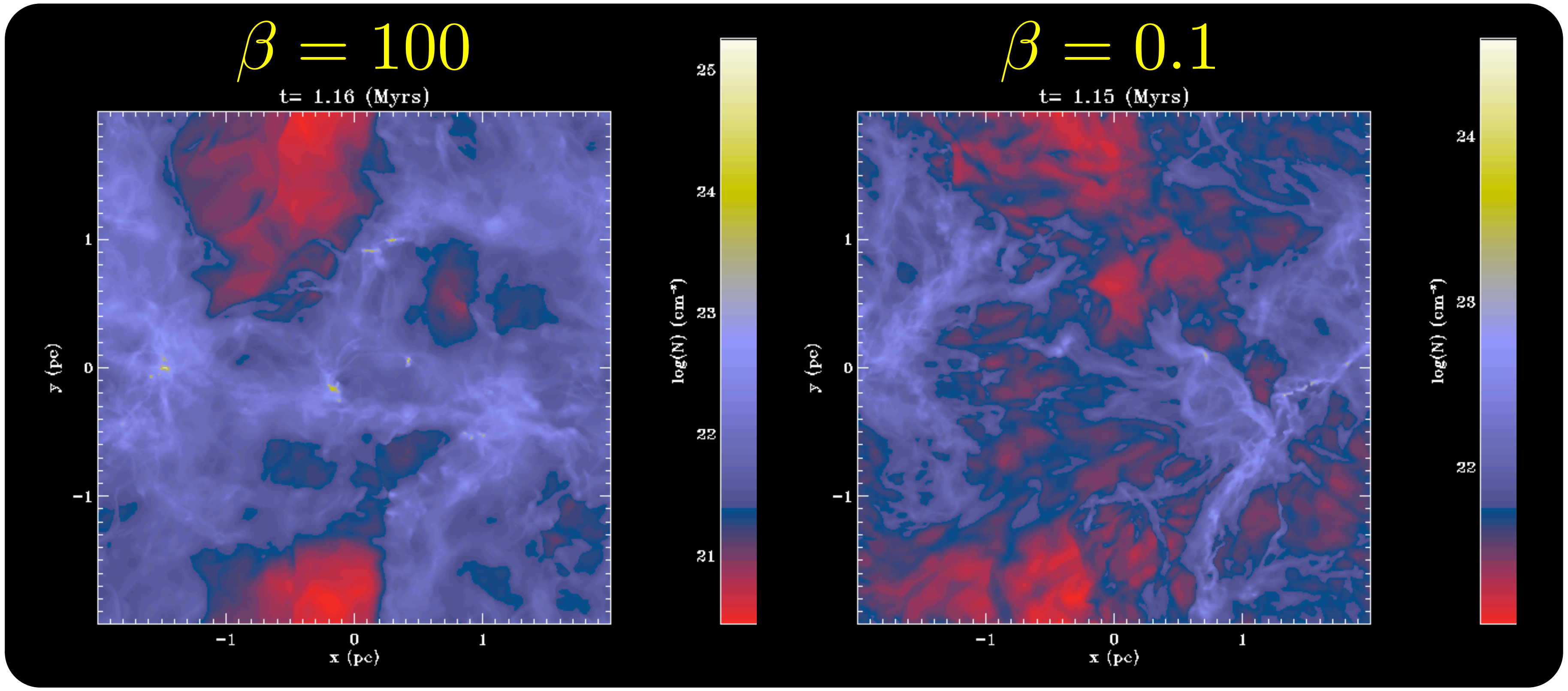
Contacts : Patrick Hennebelle, Sami Dib, Edouard Audit

Scientific case for the simulations : This project aims at describing the evolution of a turbulent molecular cloud in which the turbulence is decaying.

Description of the simulations : Initially the gas density and the magnetic field are uniform while a turbulent velocity field is setup. Turbulence is not driven and is therefore decaying during the cloud evolution. The box is periodic in all directions. Self-gravity is included and the gas is assumed to be isothermal. Under the influence of compressible modes and gravity, density fluctuations are generated. Some of them are self-gravitating and collapse. This project is well suited to compare with dense regions of molecular clouds in which stars are or will be formed. In particular, the strength of the magnetic field is varied and the consequences it has on the clouds can be investigated.

Column densities at t=1.16 Myrs

$$\beta = \frac{2\mu_0 n k_B T}{B^2} = \frac{P_{\rm therm}}{P_{\rm mag}}$$



Other simulations in the STARFORMAT database

PROJECT : Solenoidal vs. compressive turbulence forcing

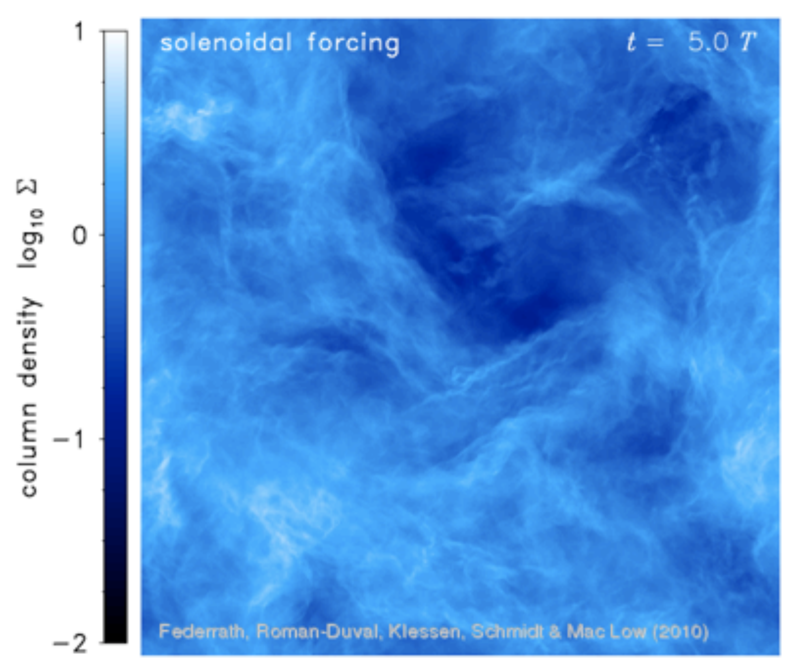
Contacts : Christoph Federrath, Julia Roman-Duval, Ralf Klessen, Wolfram Schmidt, Mordecai-Mark Mac Low

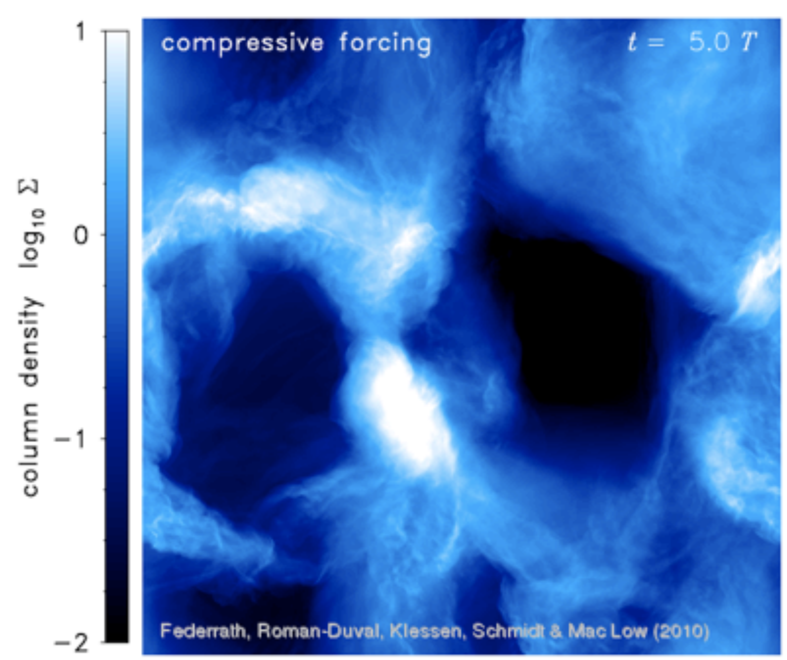
Scientific case for the simulations : This project investigates the influence of different forcing (i.e., kinetic energy injection) on turbulent flows in the ISM.

Description of the simulations : The simulations are highly simplified in the sense that periodic boundary conditions are applied in all three dimensions of the simulation and a forcing generator is used to drive the turbulence in this box. This forcing generator is constructed such that it excites correlated turbulent fluctuations on large scales, roughly corresponding to half the box size. The turbulence then develops self-consistently on smaller scales and can be studied in terms of temporal and spatial statistics. Two limiting cases of forcing are provided : solenoidal (divergence-free) and compressive (curl-free).

References : Federrath et al. 2008, ApJ 688, L79, Federrath et al. 2009, ApJ 692, 364, Federrath et al. 2010, A&A 512, A81

Code reference and description : The simulations have been performed with the FLASH3 code. This is a 3D AMR code for hydrodynamic and MHD studies with multi-physics capabilities.





Simulations to be added to the database

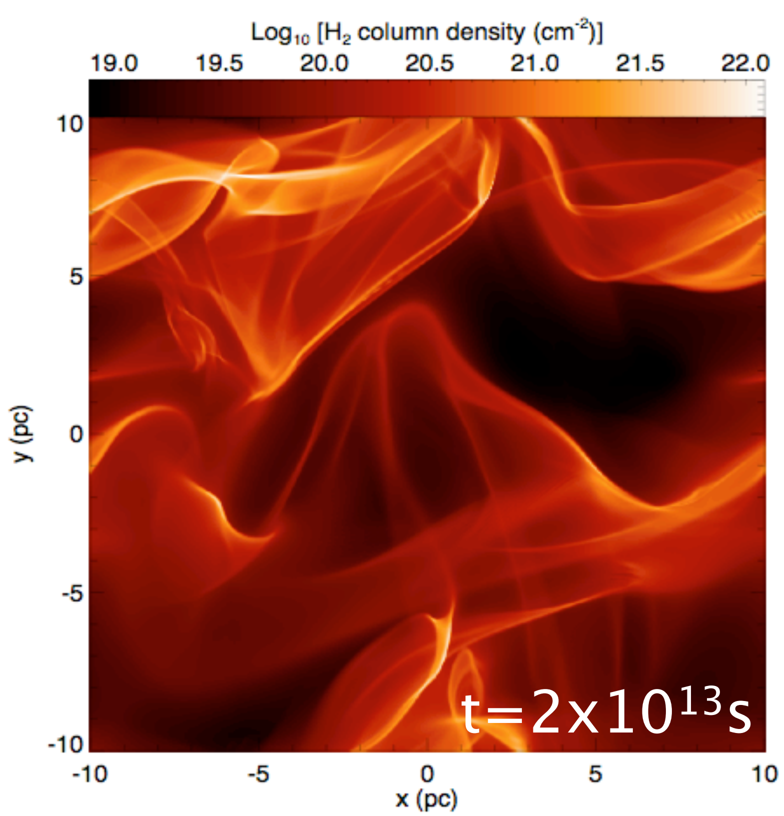
PROJECT : Chemistry simulations in the dynamic ISM

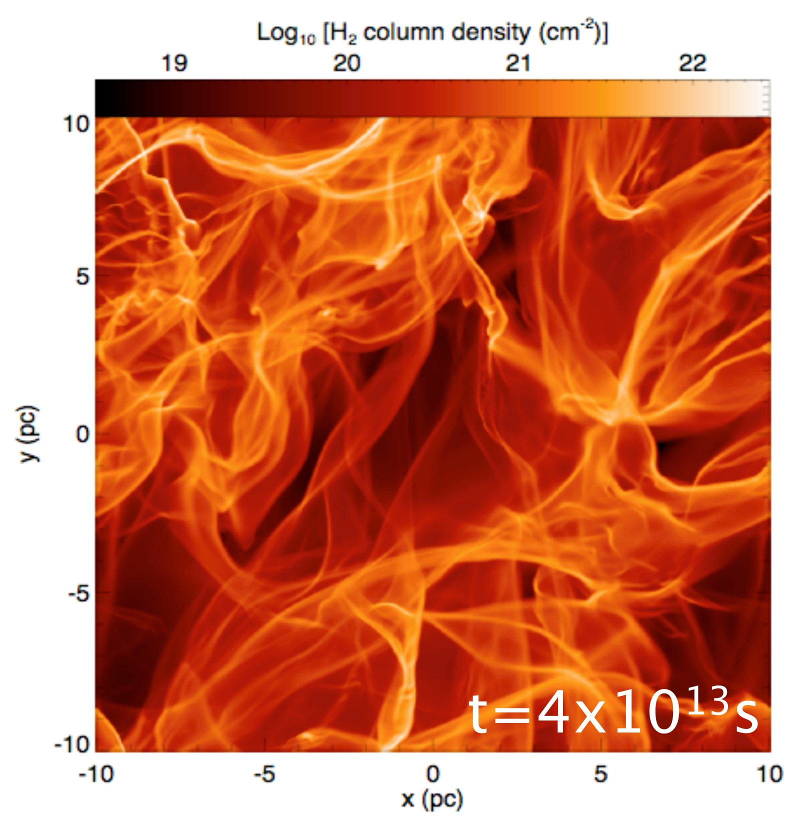
Contacts : Simon Glover, Faviola Molina, Christoph Federrath, Ralf Klessen

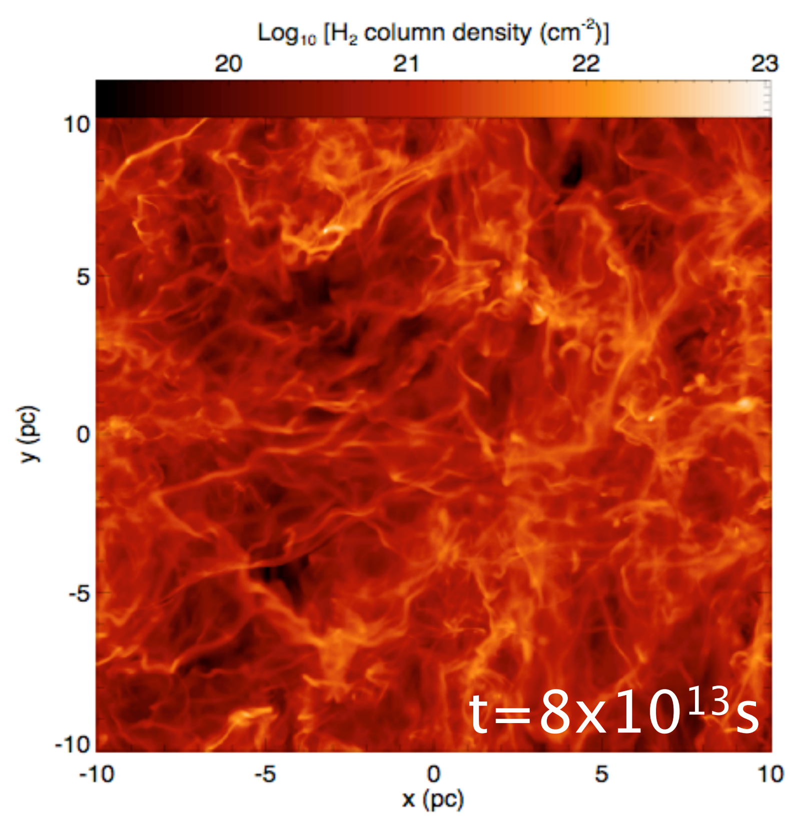
Scientific case for the simulations : Consistent models of ISM dynamics require simultaneous treatment of chemical reactions and radiative transfer, in particular with respect to the formation of molecular hydrogen.

Description of the simulations : The simulations include MHD and turbulent forcing, a simplified network of time-dependent chemistry, focussing on a few dominant species, e.g. H_2, which forms rapidly in shocks and gets slowly destroyed in low density regions. Consequently, turbulence greatly enhances the formation rate of molecular hydrogen.

References : Glover & Mac Low 2007, ApJ, 659, 1317







Simulations to be added to the database

PROJECT : Core collapse simulations

→ **Contacts :** Marc Joos, Patrick Hennebelle, Benoît Commerçon

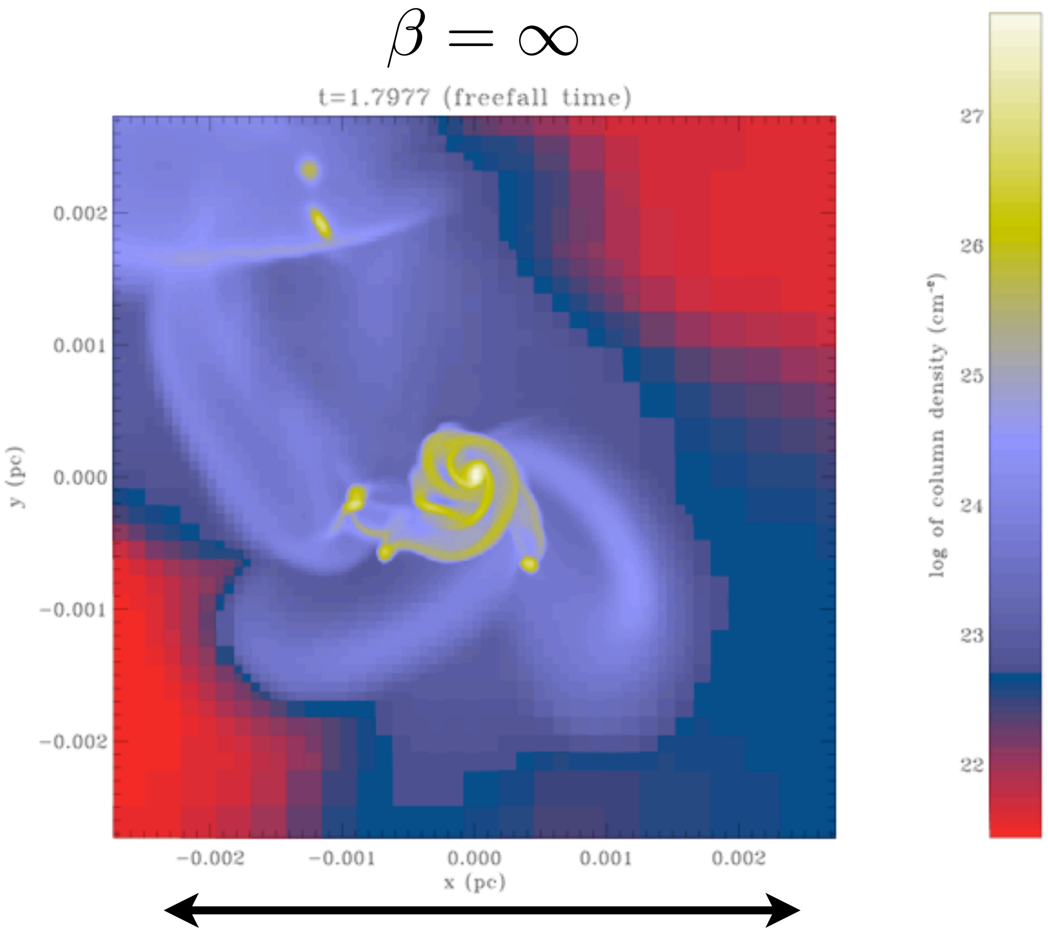
→ **Scientific case for the simulations :** The simulations describe the collapse of dense cores under their self-gravity, and aim to study the influence of turbulence and magnetic field in the process of fragmentation leading to the formation of several prestellar objects.

Thrity-solar-mass cloud initally near virial equilibrium with

$$E_{\text{turb}} = E_{\text{grav}}$$

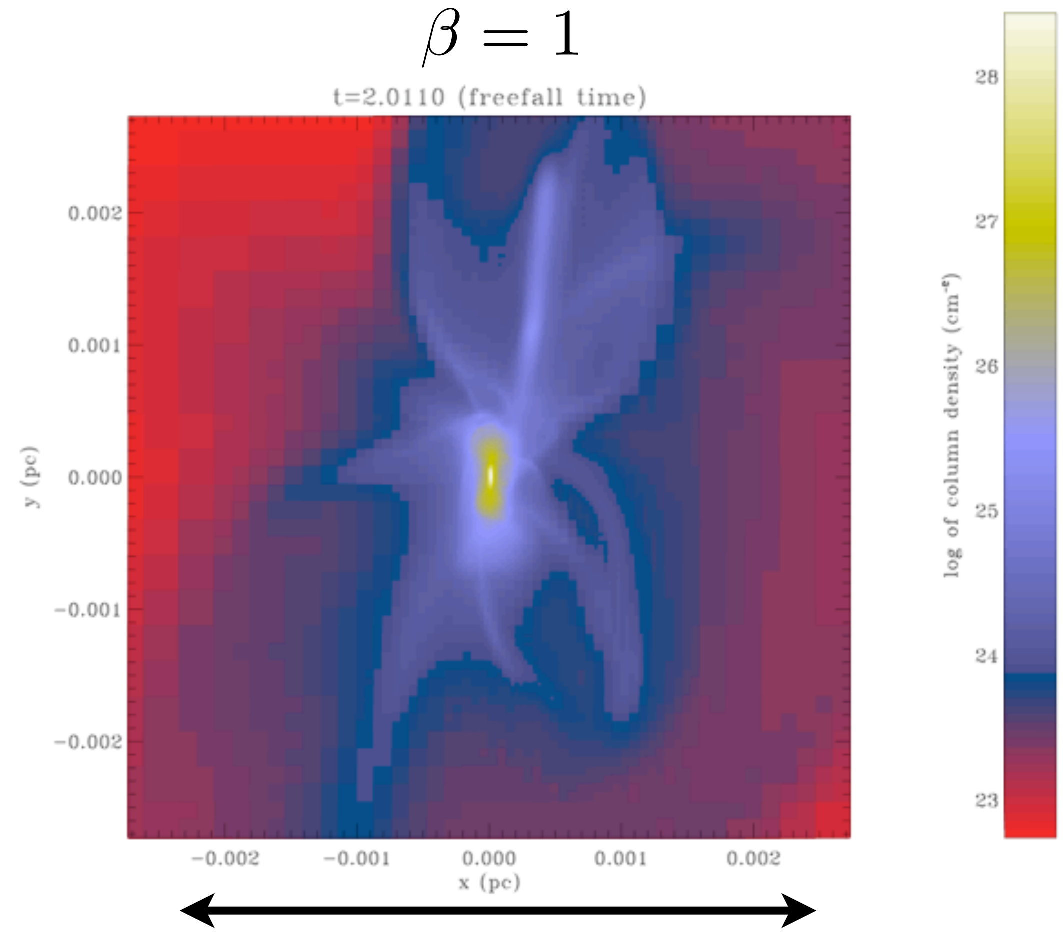
(No magnetic field)

$\beta = \infty$



0.005 pc

$\beta = 1$



0.005 pc

Allen et al. 03, Machida et al. 05, 07, 08, Fromang et al. 06, Galli et al. 06, Banerjee & Pudritz 06, Hennebelle & Fromang 08, Hennebelle & Teyssier 08, Price & Bate 07,08, Mellon & Li 08, 09

Overview of the talk

The project

- Scientific context and questions
- Overview of the project
- Structure of the database

An example simulation : converging flows

- Accessing simulation results
- Statistics of "clumps" and comparison with observational data
- On-the-fly clump extraction
- Post-processed radiative transfer with RADMC-3D
- The other simulations in the database

Post-processed chemistry on MHD simulations

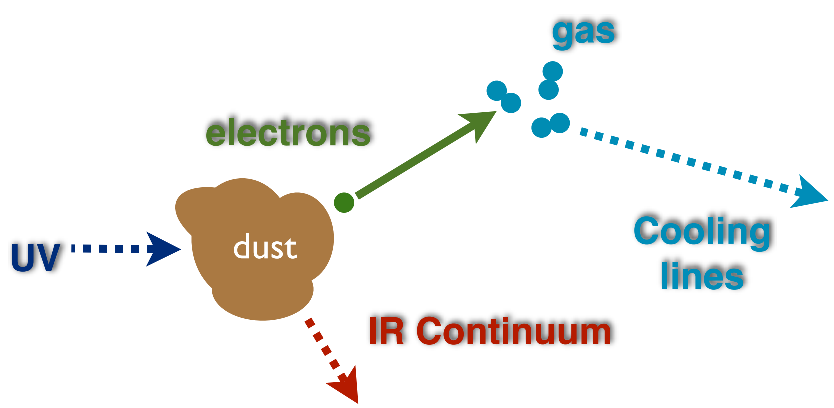
- Application of the Meudon PDR code on lines of sight through MHD simulation cubes
- Evidence for "dark" molecular gas, not seen in CO
- Further ideas beyond the 1D PDR code

Simulated ALMA observations with GILDAS

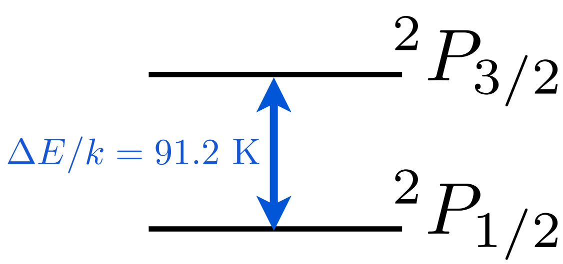
- Simulated observations of large-scale MHD flows
- Simulated observations of collapsing cores
- Interpretation of observations

Detailed chemistry on MHD simulations

A case study : the 158 µm [CII] line

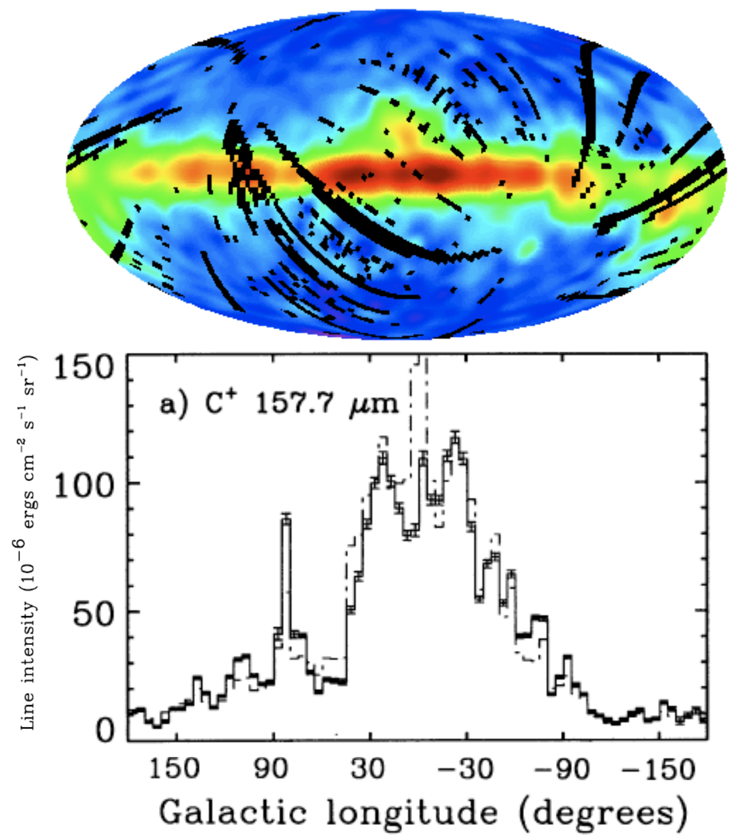


UV to IR energy transfer via photoelectric effect

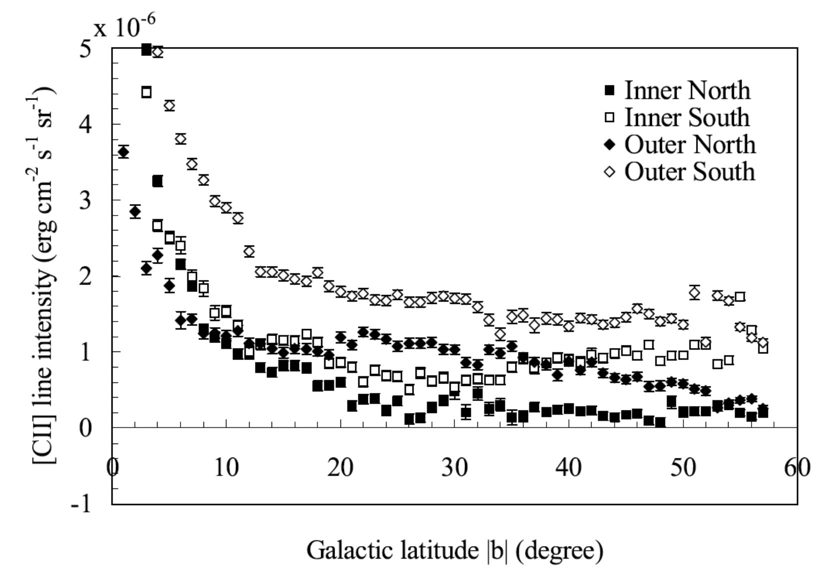


Fine structure of the ground state of C+

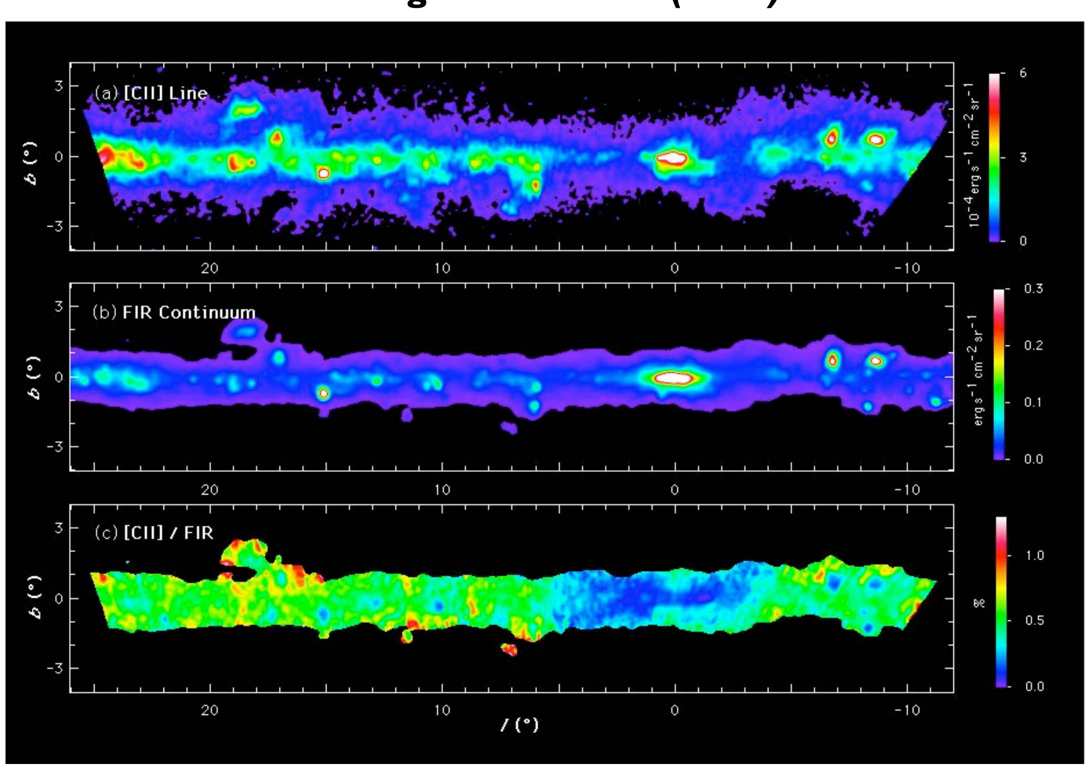
Bennett et al. 94 (COBE / FIRAS)



Makiuti et al. 2002 (FILM / IRTS)



Nakagawa et al. 98 (BICE)



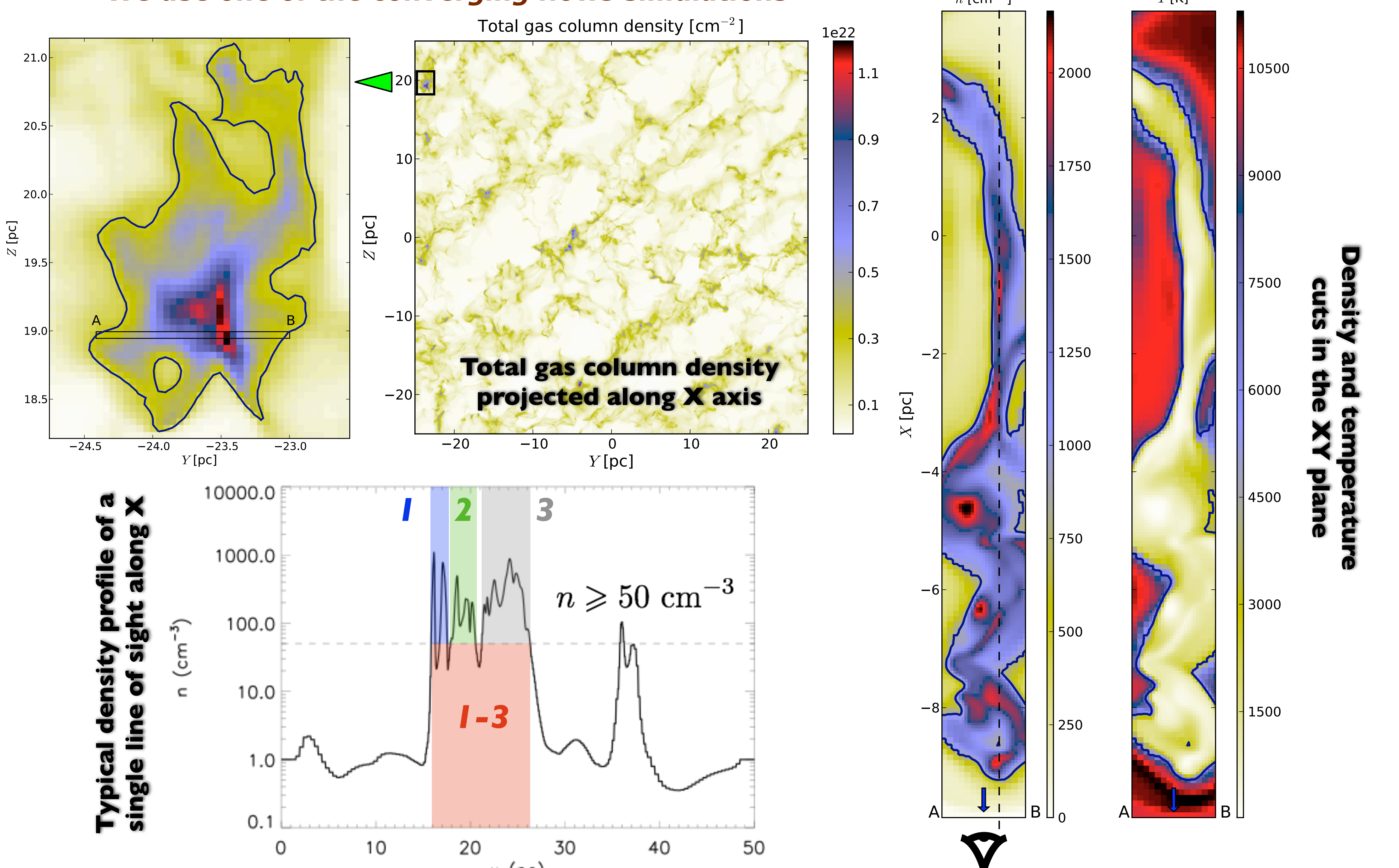
Carbon ionization potential 11.3 eV, so potentially exists where hydrogen is neutral, or even molecular

One of the dominant cooling lines of interstellar gas

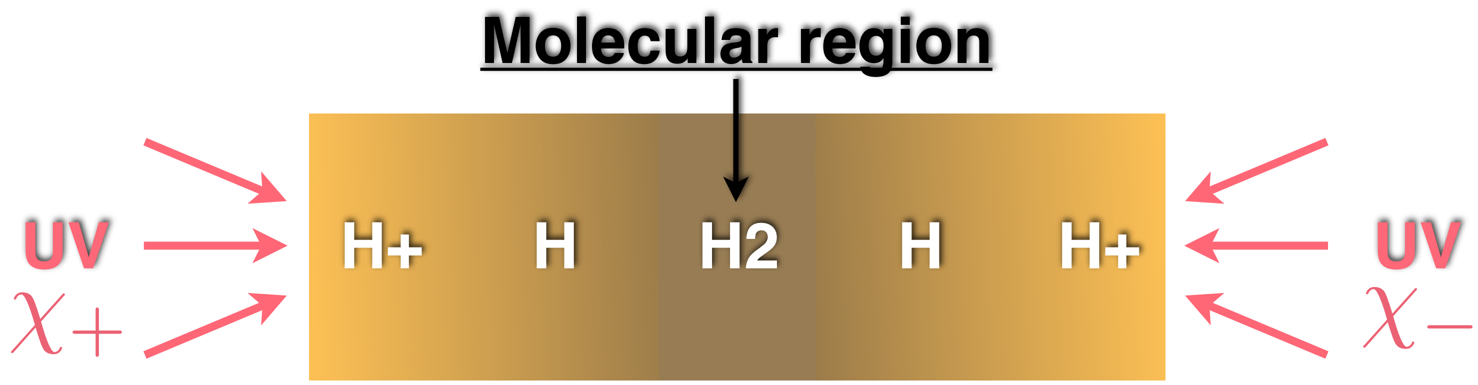
Detailed chemistry on MHD simulations

Method : Extract one-dimensional lines of sight through a simulation cube and run the PDR code on these.

We use one of the converging flows simulations



The Meudon PDR code



http://pdr.obspm.fr/

Le Bourlot et al. 1999
Le Petit et al. 2006
Goicoechea & Le Bourlot 2007
Gonzalez-Garcia et al. 2008

Stationary 1D model, including :

- UV radiative transfer:
  - Absorption in molecular lines
  - Absorption in the continuum (dust)
  - 10000's of lines
- Chemistry :
  - Several hundred chemical species
  - Network of sevral thousand chemical reactions
  - Photoionization
- Statistical equilibrium of level populations
  - Radiative and collisional excitations and de-excitations
  - Photodissociation
- Thermal balance:
  - Photoelectric effect
  - Chemistry
  - Cosmic rays
  - Atomic and molecular cooling

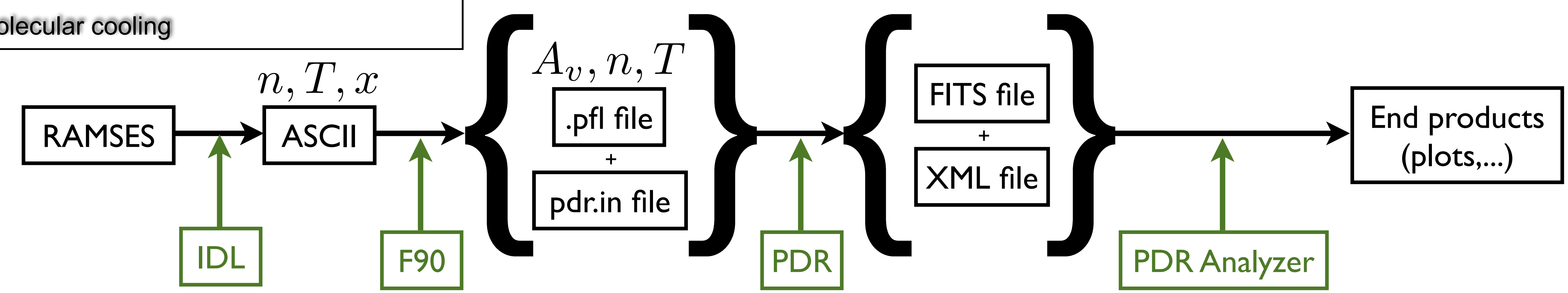
Outputs :

- Local quantities :
  - Abundance and excitation of species
  - Temperature of gas and duts
  - Detailed heating and cooling rates
  - Energy density
  - Gas and grain temperatures
  - Chemical reaction rates
- Integrated quantities on the line of sight :
  - Species column densities
  - Line intensities
  - Absorption of the radiation field
  - Spectra

and also :

E. Roueff
P. Hily-Blant
S. Guilloteau
C. Joblin
G. Pineau des Forêts
[...]

RAMSES to PDR pipeline :

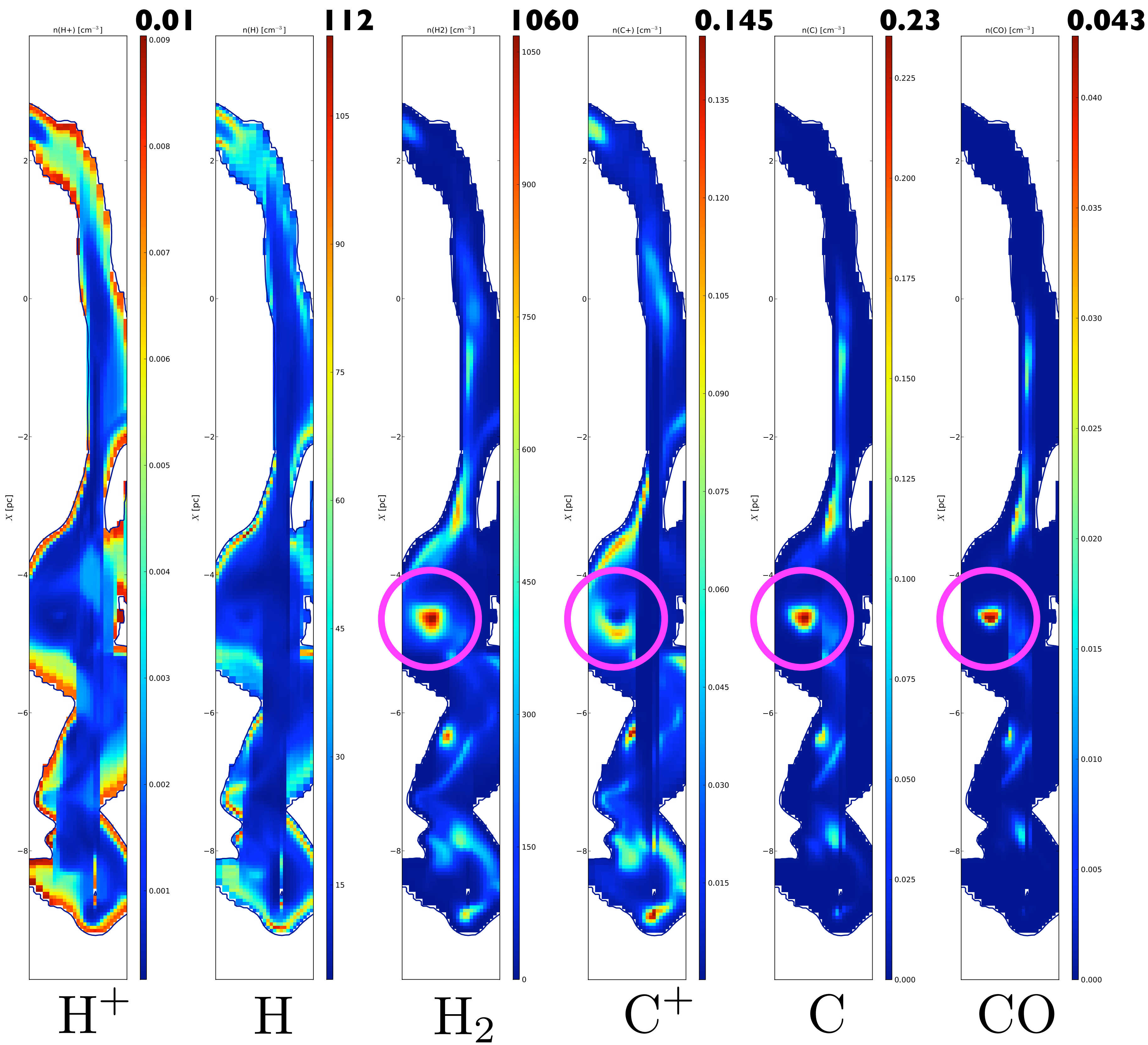


Convergence issues in low density regions → Apply code on overdensities only

Heavy computations : a few hours per "clump" → Grid computation would be ideal

“Dark gas”

Abundances computed by the PDR code in the XY plane

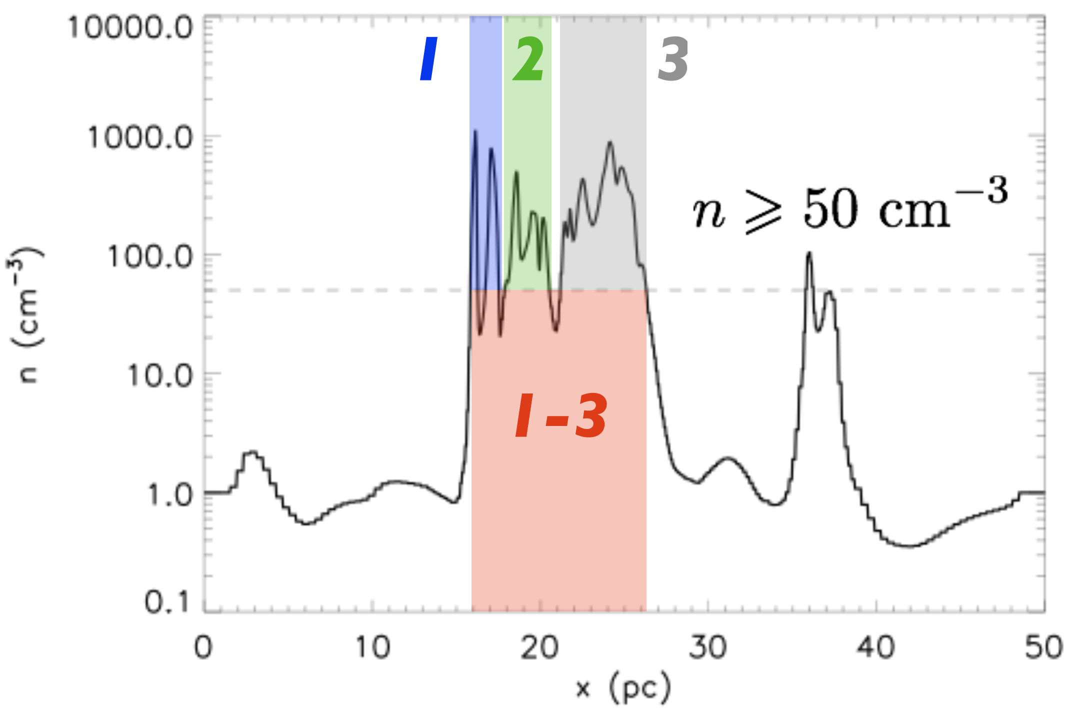


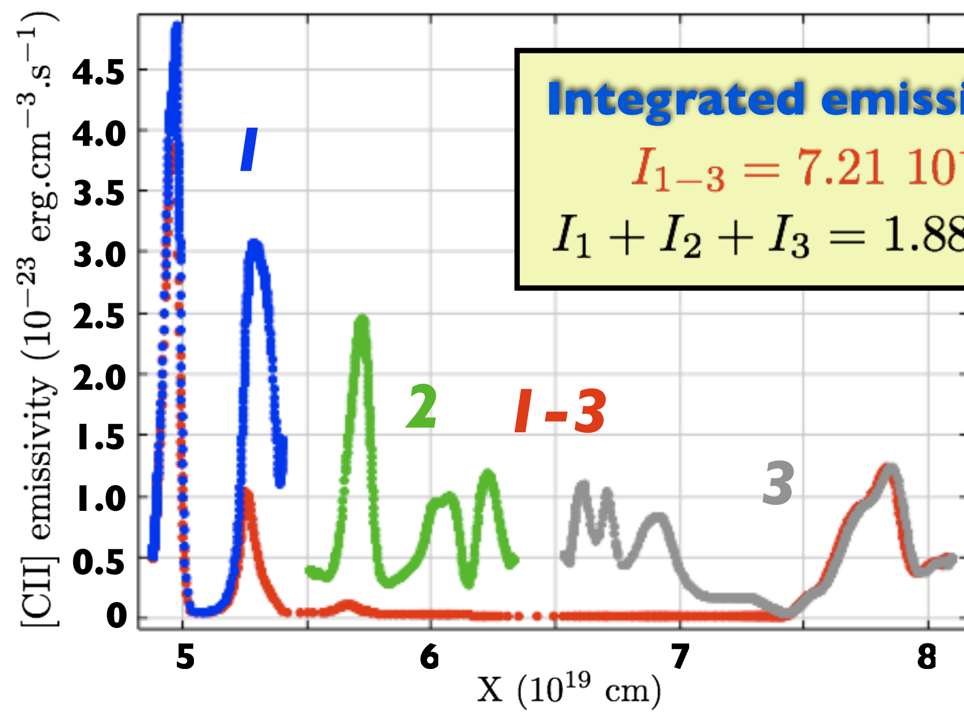
Levrier et al. (in prep)

A significant fraction of the molecular region is not seen in CO, but rather traced by C or C+

Artificial “stripes” due to shadowing in the one-dimensional PDR code

Beyond the 1D PDR code





Integrated emissivity of the [CII] line

$I_{1-3} = 7.21\ 10^{-6} \mathrm{erg.cm^{-2}.s^{-1}.sr^{-1}}$

$I_1 + I_2 + I_3 = 1.88\ 10^{-5} \mathrm{erg.cm^{-2}.s^{-1}.sr^{-1}}$

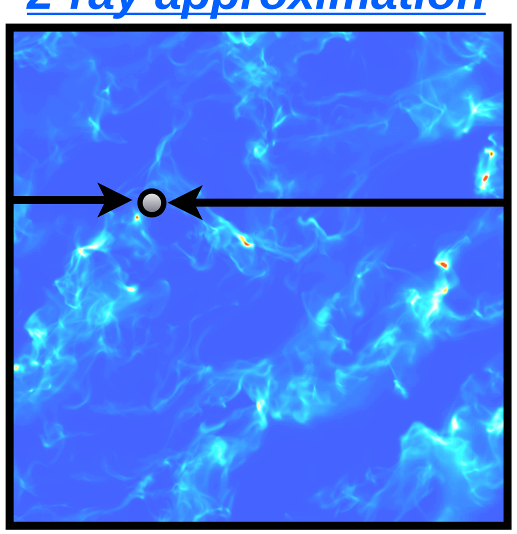
1D geometry unrealistic

Possible lines of work...

Split 1D profiles in substructures and compute local illumination using a mean local UV field (possibly on the fly in RAMSES simulations)

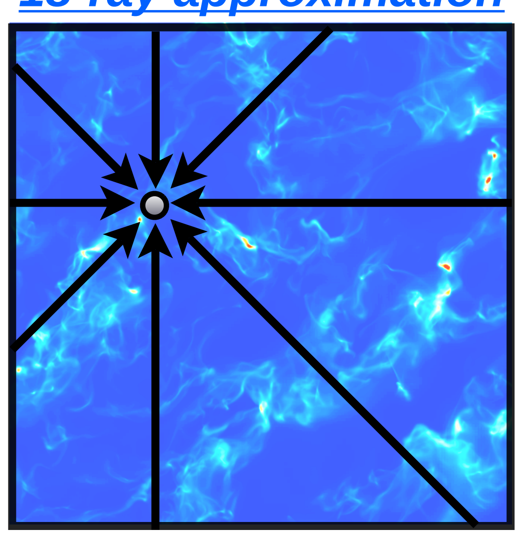
$$\chi \propto \langle \exp\left(-\alpha A_v\right) \rangle$$

2-ray approximation



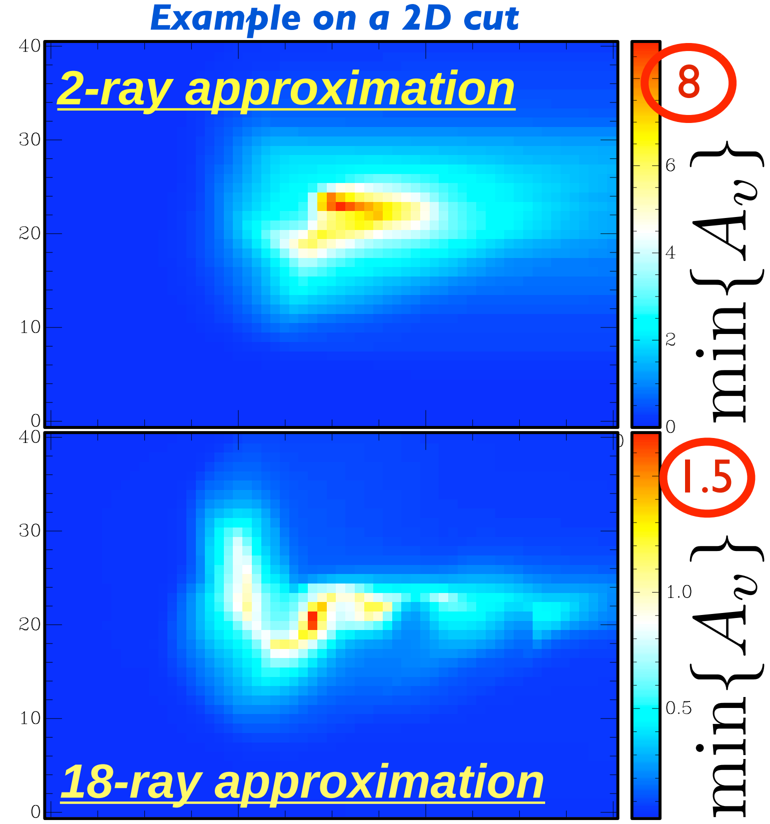
(1D : same as PDR code)

18-ray approximation

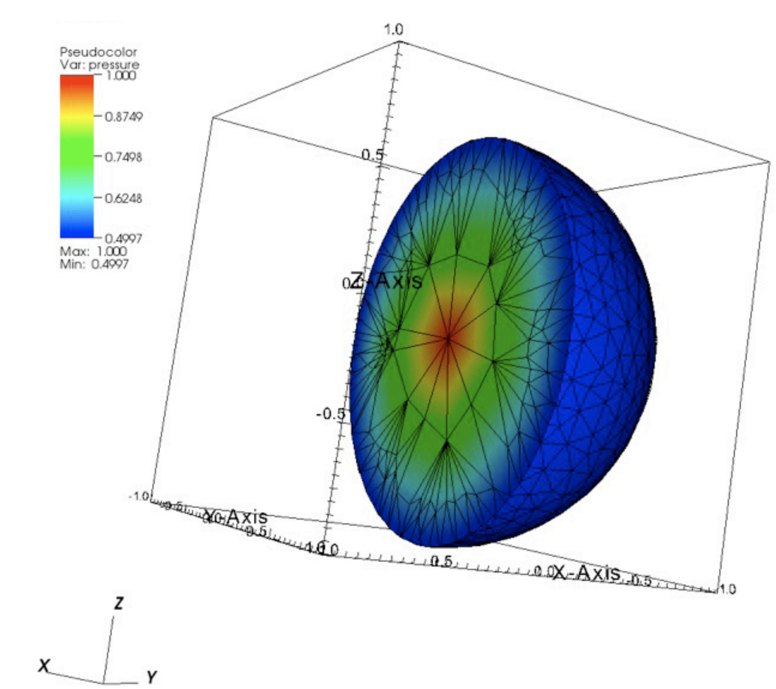


(in each of XY, XZ, YZ planes)

Example on a 2D cut



Development of a 3D PDR code using Voronoi tessellation (Cecilia Pinto)



Overview of the talk

The project

- Scientific context and questions
- Overview of the project
- Structure of the database

An example simulation : converging flows

- Accessing simulation results
- Statistics of "clumps" and comparison with observational data
- On-the-fly clump extraction
- Post-processed radiative transfer with RADMC-3D
- The other simulations in the database

Post-processed chemistry on MHD simulations

- Application of the Meudon PDR code on lines of sight through MHD simulation cubes
- Evidence for "dark" molecular gas, not seen in CO
- Further ideas beyond the 1D PDR code

Simulated ALMA observations with GILDAS

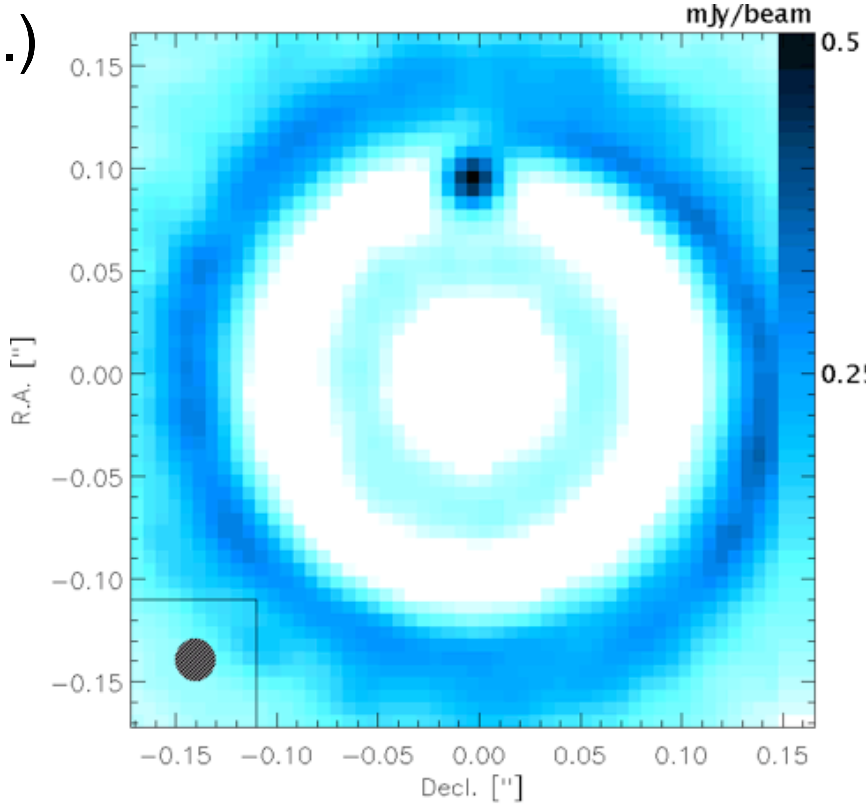
- Simulated observations of large-scale MHD flows
- Simulated observations of collapsing cores
- Interpretation of observations

The ALMA Simulator in GILDAS

An **ALMA / ALMA Compact Array (ACA) / Single Dish** imaging simulator

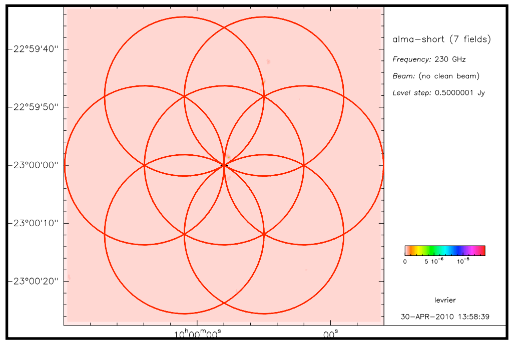
- Detailed description in ALMA memo 398 (Pety, Gueth, Guilloteau)
- Developed for studying the impact of ACA on wide-field imaging capabilities
- Scientific preparation of ALMA (e.g. Wolf et al.)
- Included in GILDAS' MAPPING software

http://www.iram.fr/IRAMFR/GILDAS/



1. Inputs

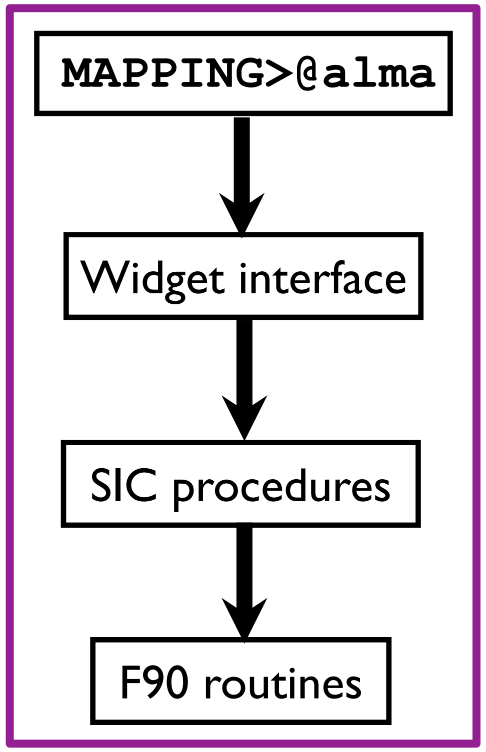
- Source position and size : mosaicing →
- Model brightness distribution
- Array configuration
- Frequency **(only continuum)**
- Type of observation (ALMA + ACA + Single Dish)



2. Visibilities

$$\text{Visibilities} = \text{Cover} \times \text{FT}[\text{Beam} \times \text{Model}]$$

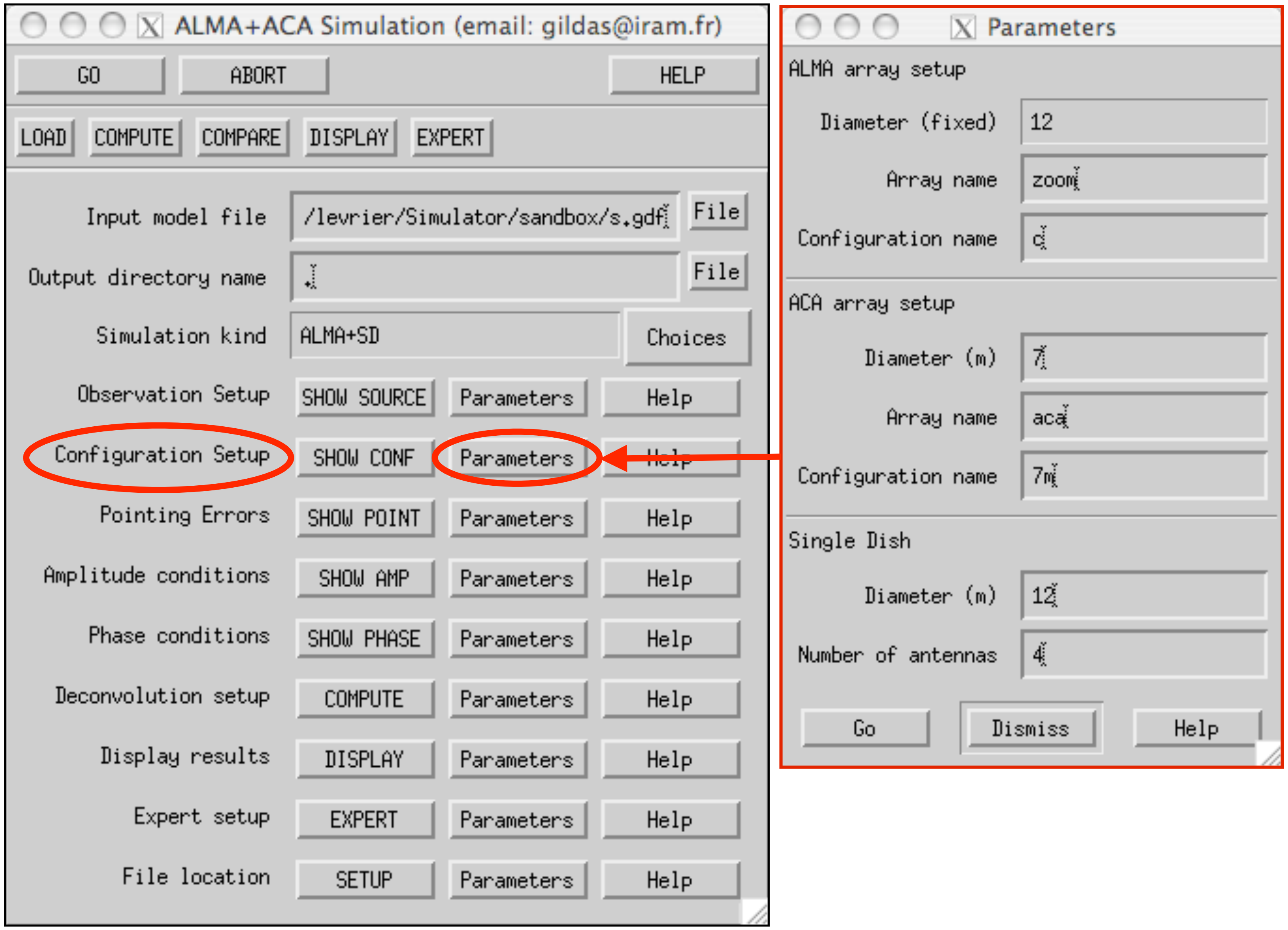
- Cover from source position, array configuration and time range
- Beam from antenna size
- Source-calibrator loop
- Possibility to add pointing errors, atmospheric phase noise, calibration errors

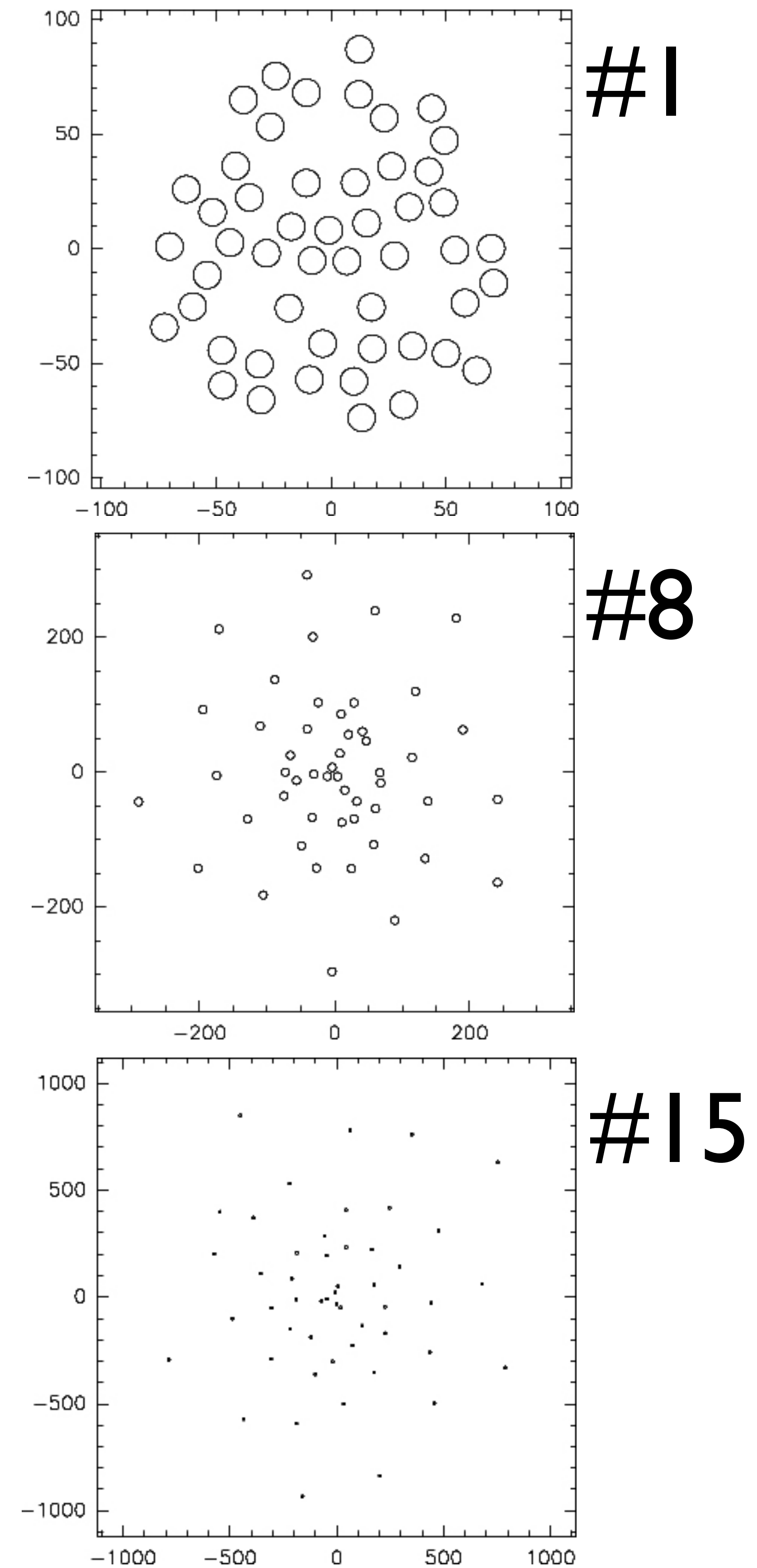


3. Imaging

- Calibration (standard, fast switching, water vapor radiometry)
- Deconvolution (Standard CLEAN based methods)
- Input and output comparison

Up-to-date ALMA configurations

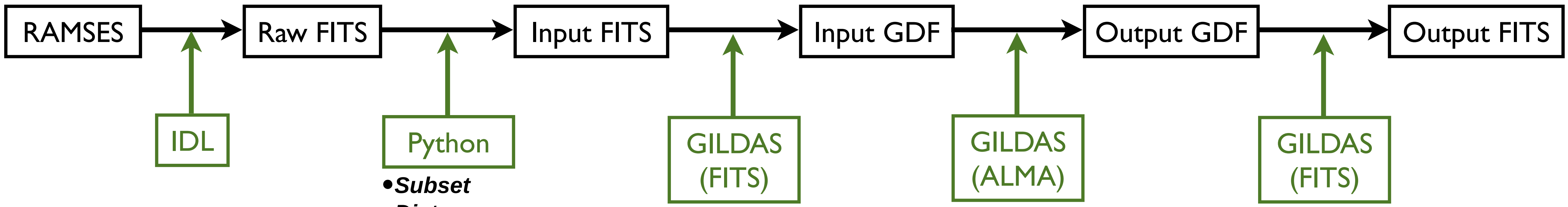




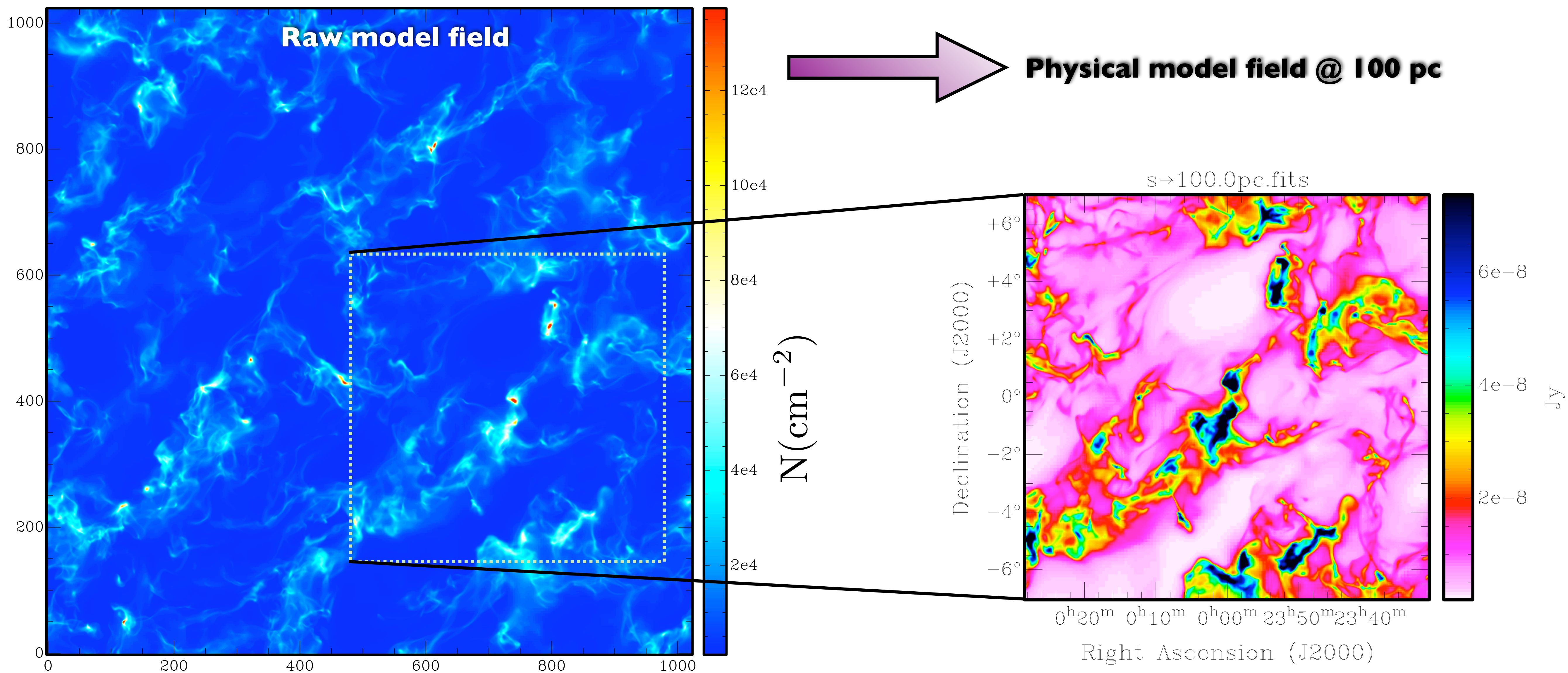
- *28 configurations*
- *From 90 m to 9.5 km radius*
- *CASA to GILDAS format conversion*

Thanks to J. Pety, A. Wooten, I. Heywood, K.-I. Morita

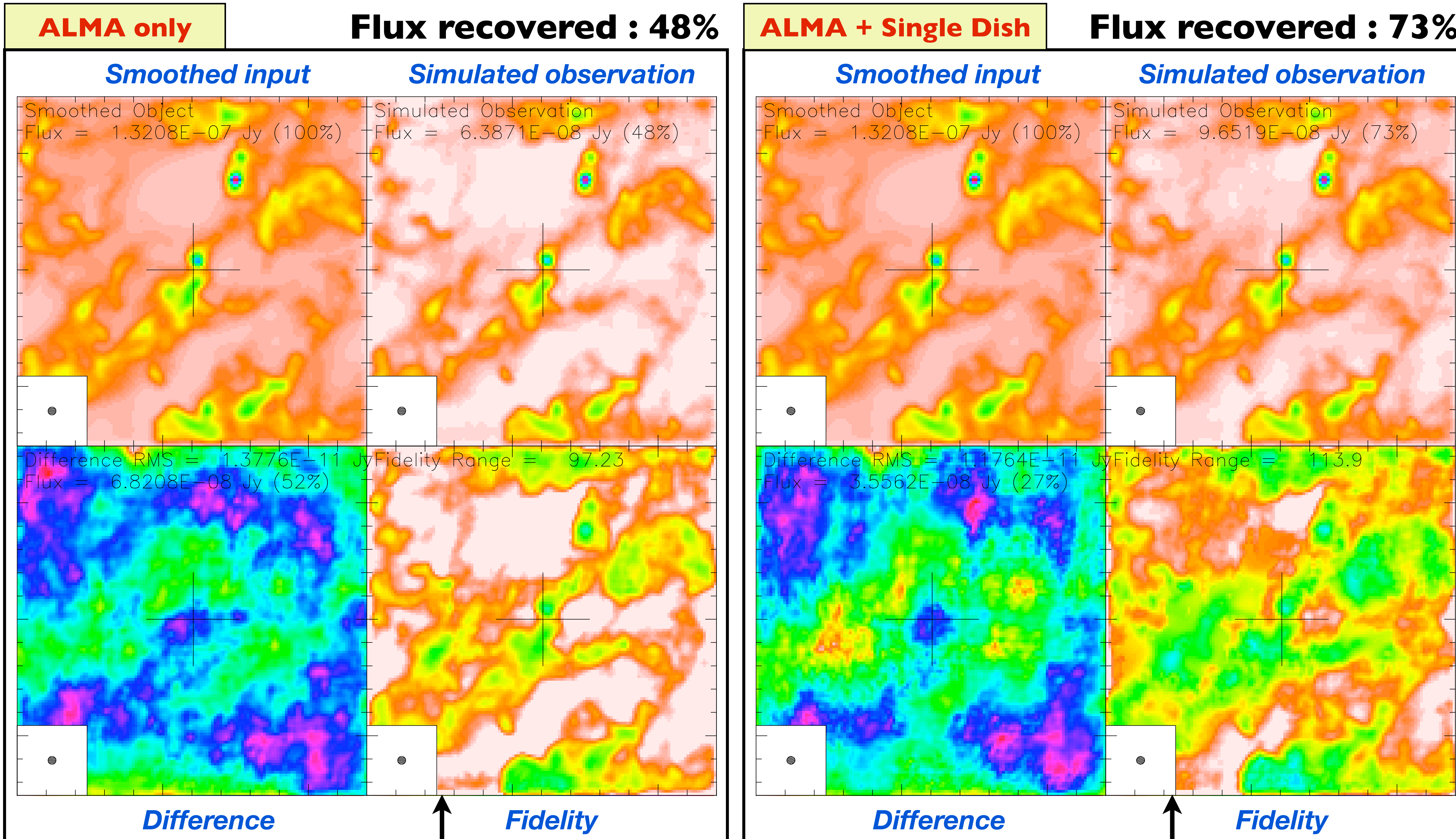
ALMA simulator on MHD simulations



- ***Subset***
- ***Distance***
- ***Brightness temperature***
- ***Sky position***



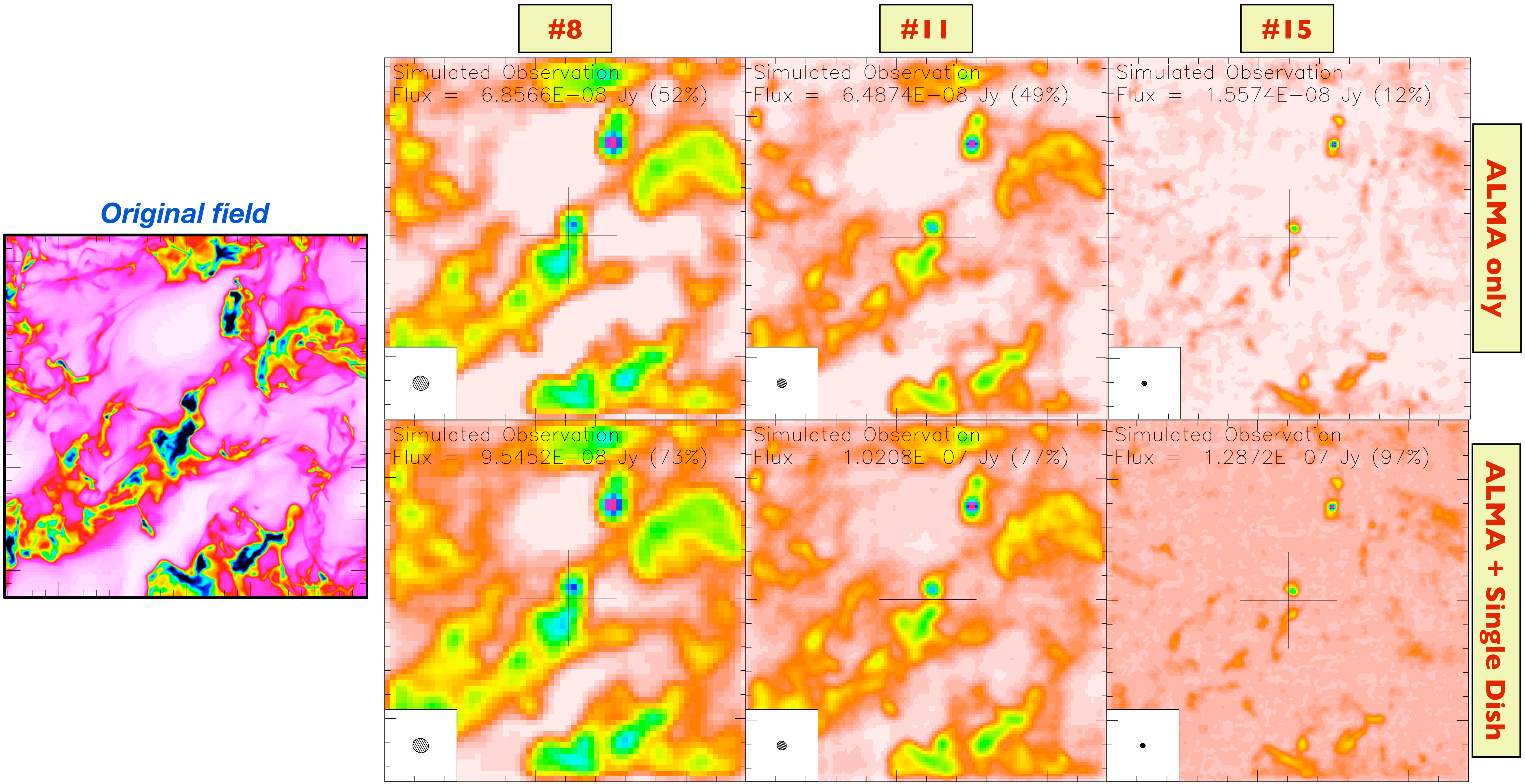
Simulated observations of large-scale flows



Fidelity image = input model / difference

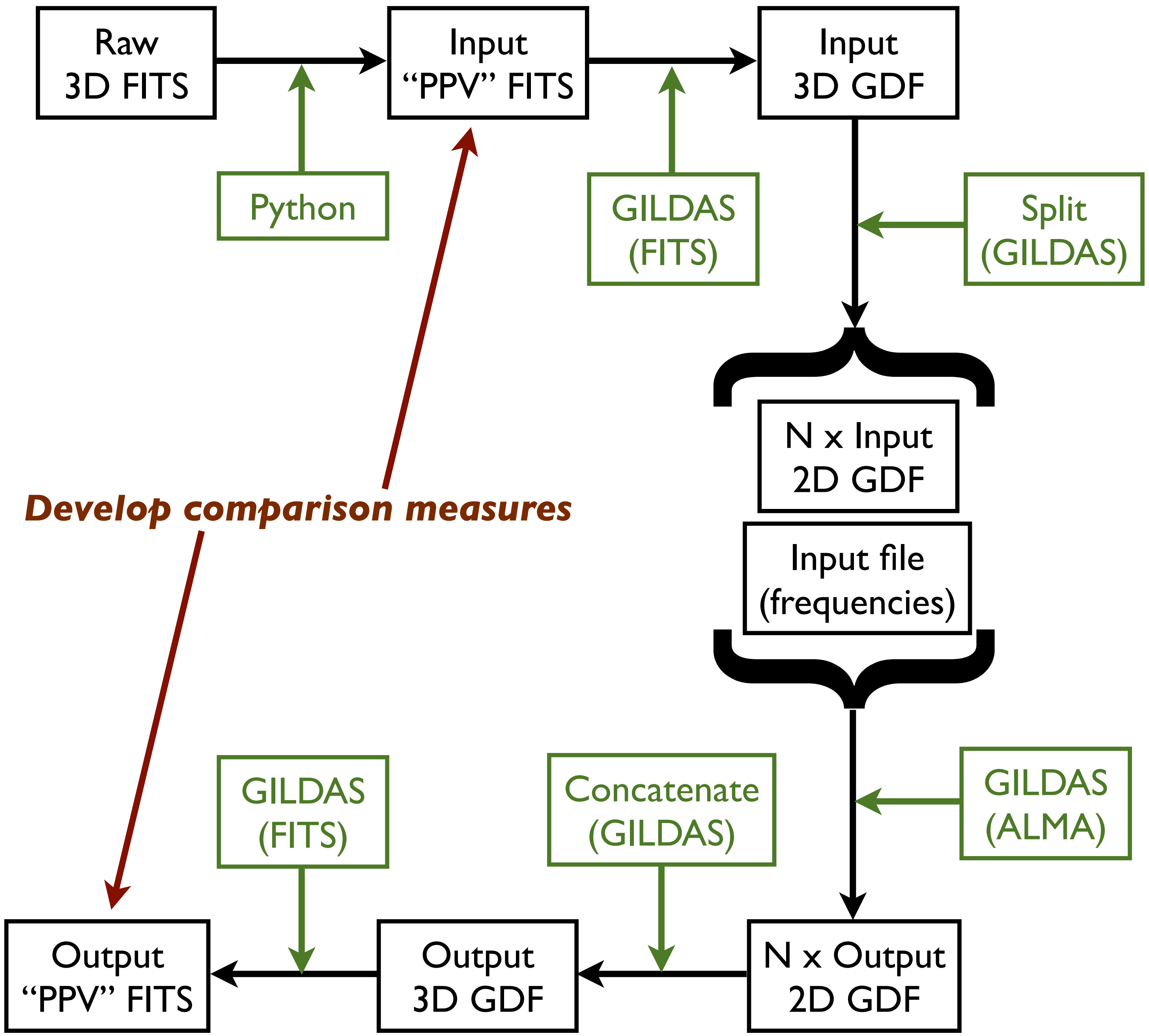
- **Inverse of relative error**
- **In practice, lowest values of difference are truncated**

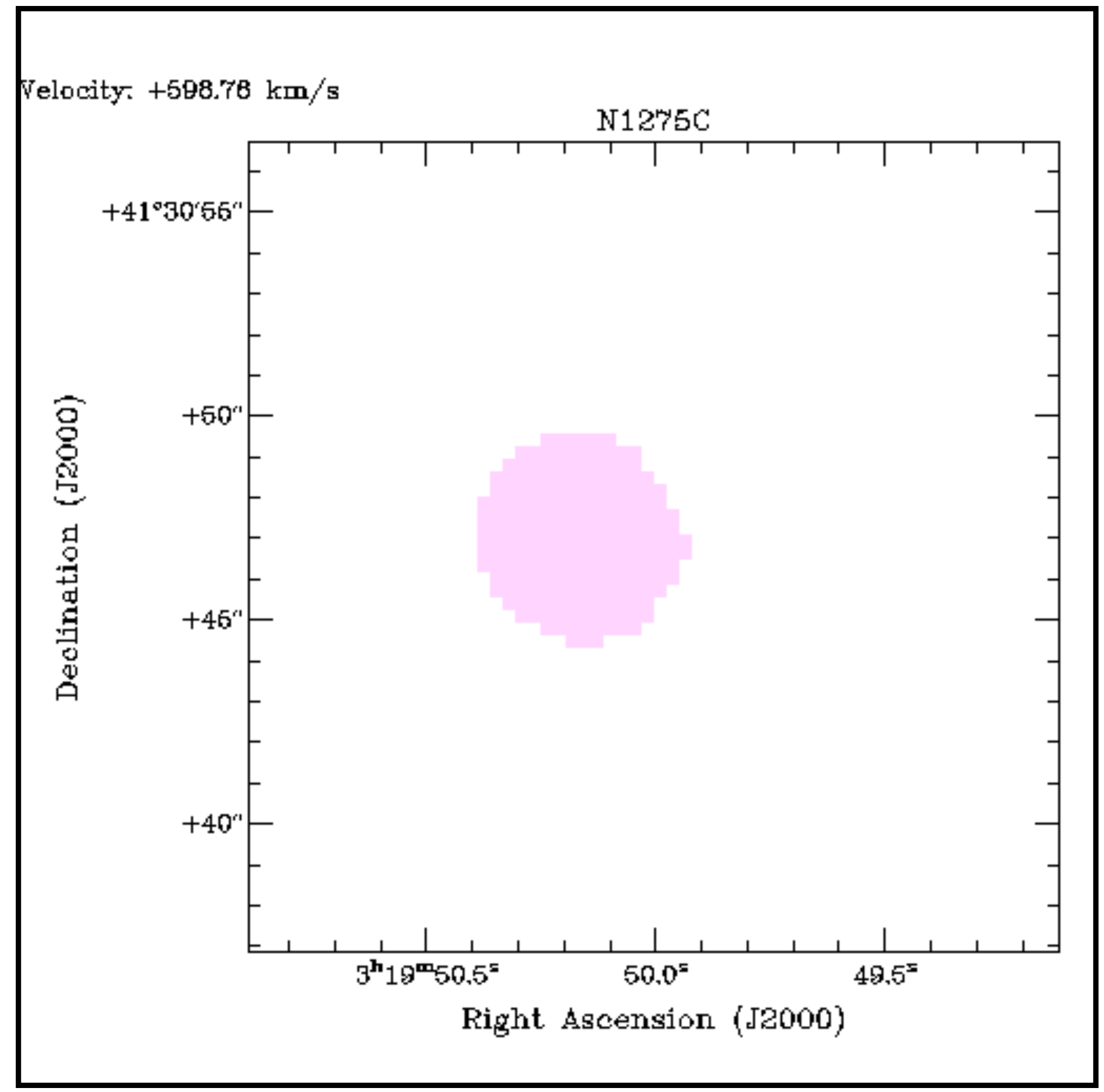
Simulations for different configurations



- Spatial frequency filtering
- Flux loss
- Importance of single-dish measurements

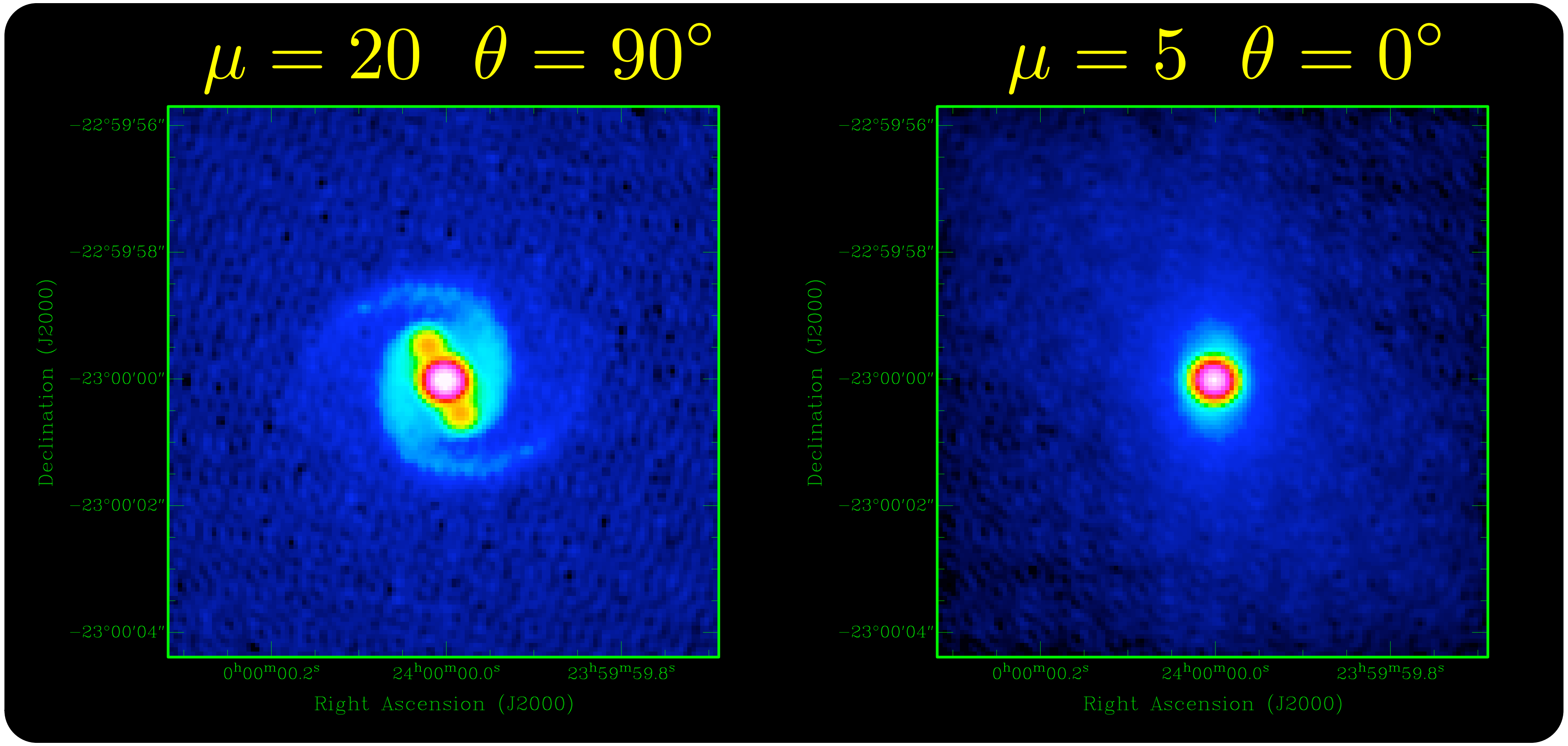
“Line” mapping using batch mode

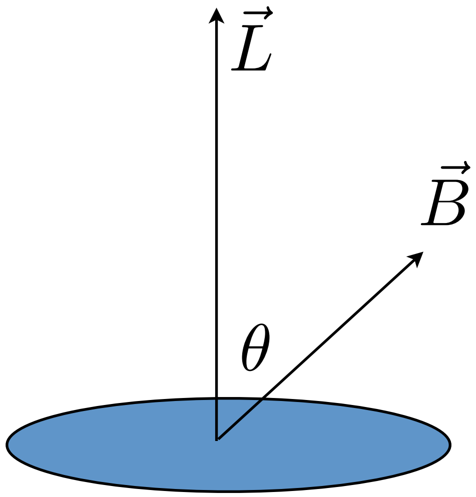




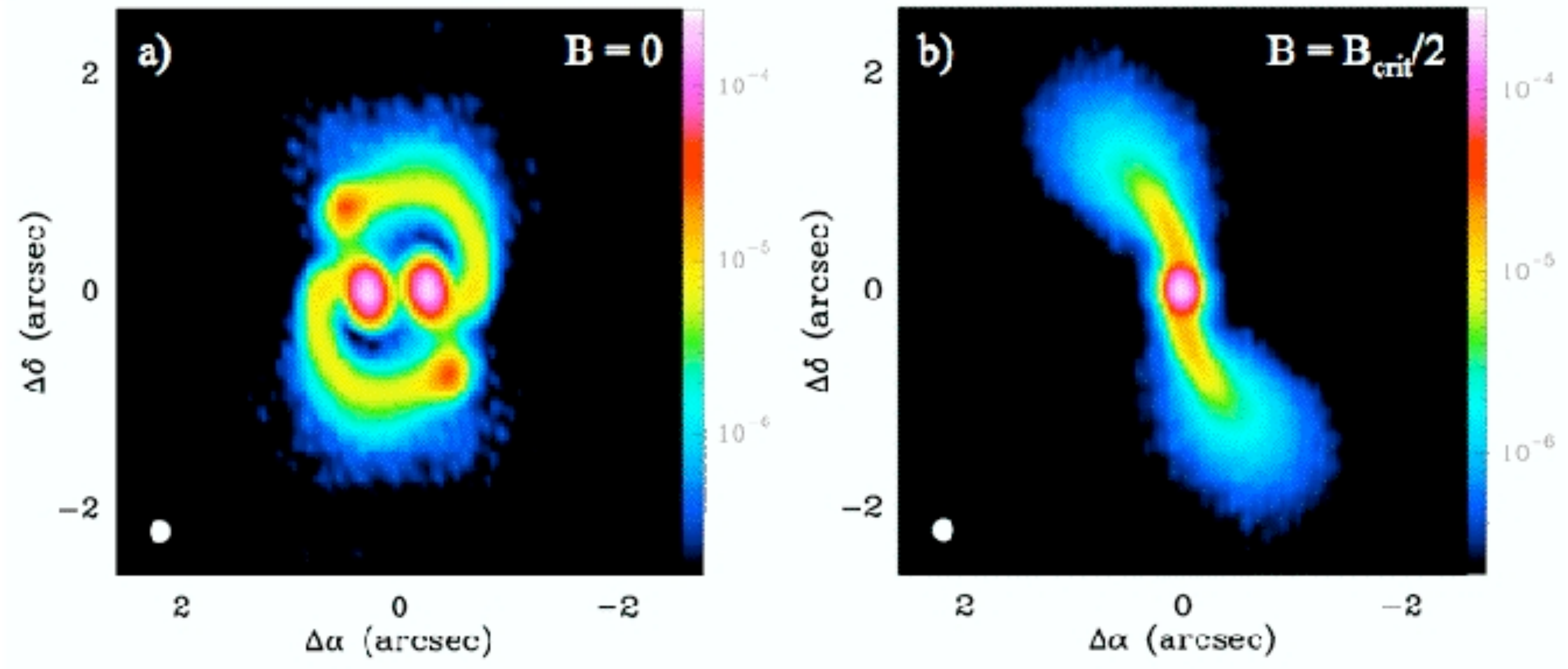
Simulated ALMA observations of collapsing cores

ALMA band 7 (.........) images for configuration #10





$$\mu = \frac{(M/\Phi)}{(M/\Phi)_{\rm crit}}$$



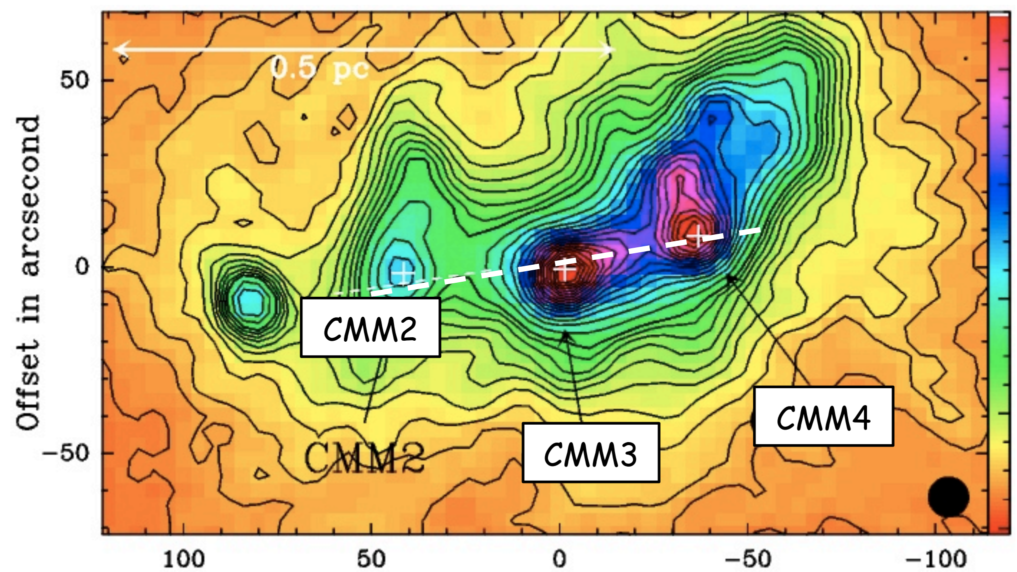
André, Hennebelle, Peretto 2008

A new path for interpreting observations

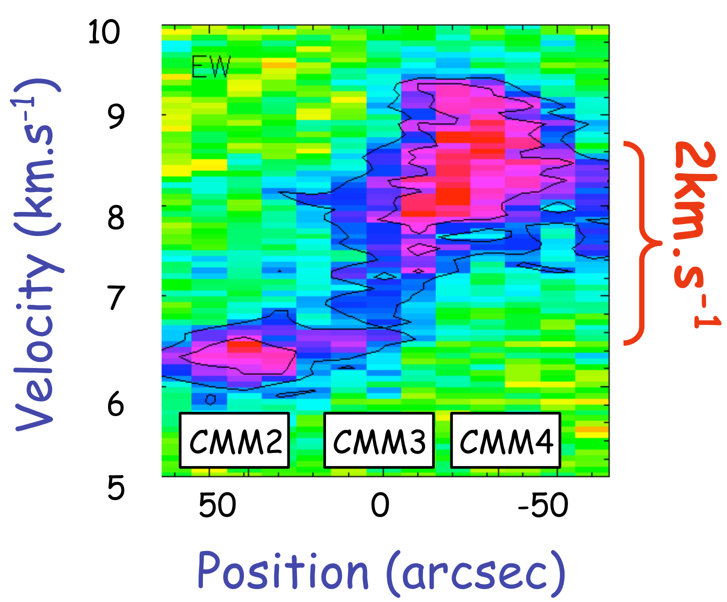
Observations with IRAM 30 m telescope

Peretto, André & Belloche, 2006

Continuum @ 1.2mm

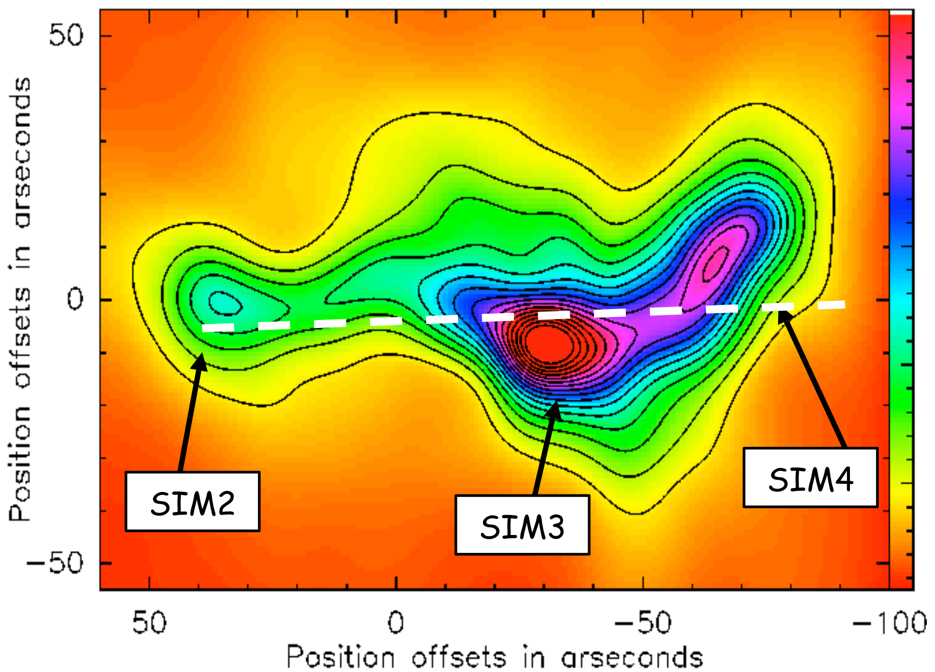


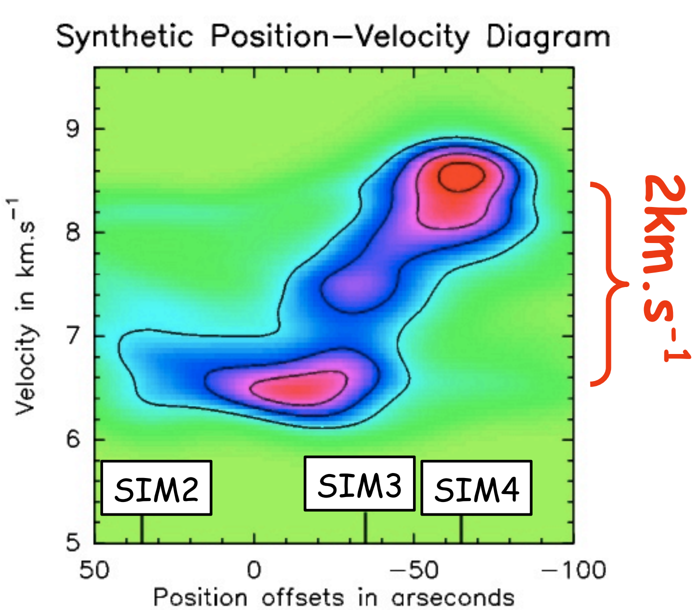
Position-Velocity diagram in the N_2H^+(101-012) line



SPH simulation with 5,000,000 particles

Peretto, Hennebelle & André, 2007





Conclusions and perspectives

An evolving database...

- A leading, long-ranging effort to bring together theoretical, numerical and observational expertise in ISM and star formation questions

- Already allows user-friendly access to several numerical simulation results,, with many more to come, using VO-compliant models and protocols

- The need for new simulations / statistics / post-processing is an evolving process, motivated by dicussions with observers and increasing computing capabilities

Perspectives

- Clean-up RAMSES/RADMC, RAMSES/PDR and RAMSES/GILDAS connections

- Develop Lagrangian particle-based approach to estimate clump lifetimes

- Open up the database to outside groups... Simulations and expertise welcome !