THE ROLE OF MAGNETIC FIELDS IN STAR FORMATION

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MAGNETIC in a nutshell

- MAGNETIC joints the efforts of theorists and observers in the Italian community with the aim of investigating the role of magnetic fields in low- and high-mass star formation.

- MAGNETIC combines observations and modeling of the magnetic field on spatial scales from cloud to core to disk and jet scales, and is based on thermal (dust and line) and maser emission polarization observations of a statistically significant sample of star-forming regions.

Team

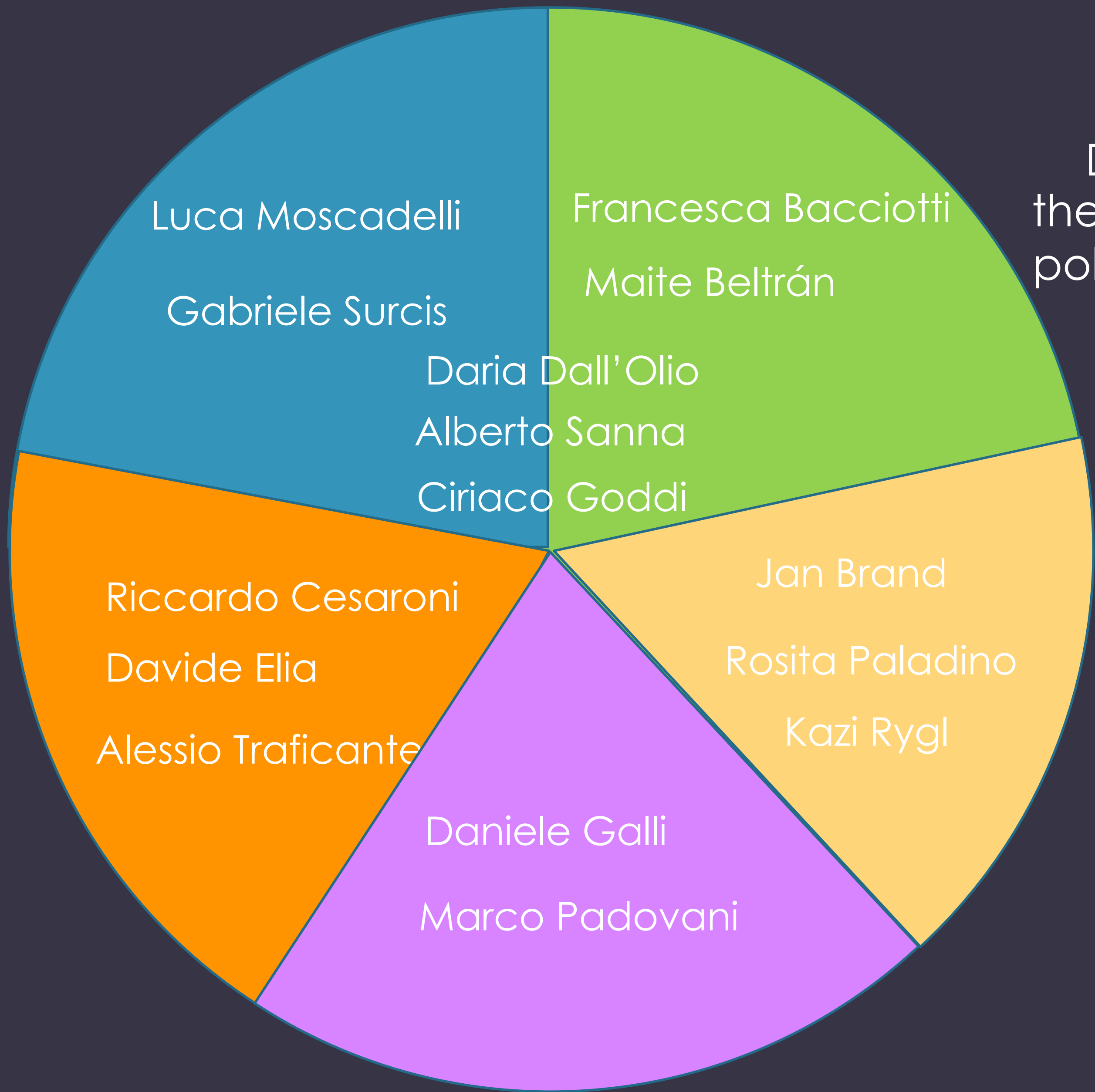
OAA

OAC

IRA

IAPS

Team



Maser polarization
Luca Moscadelli
Gabriele Surcis
Dust + thermal line polarization
Francesca Bacciotti
Maite Beltrán
Daria Dall'Olio
Alberto Sanna
Ciriaco Goddi
Kinematics
Riccardo Cesaroni
Davide Elia
Alessio Traficante
Assistance with observations + pol. calibration
Jan Brand
Rosita Paladino
Kazi Rygl
Daniele Galli
Marco Padovani
Theory + modeling

Importance of magnetic field

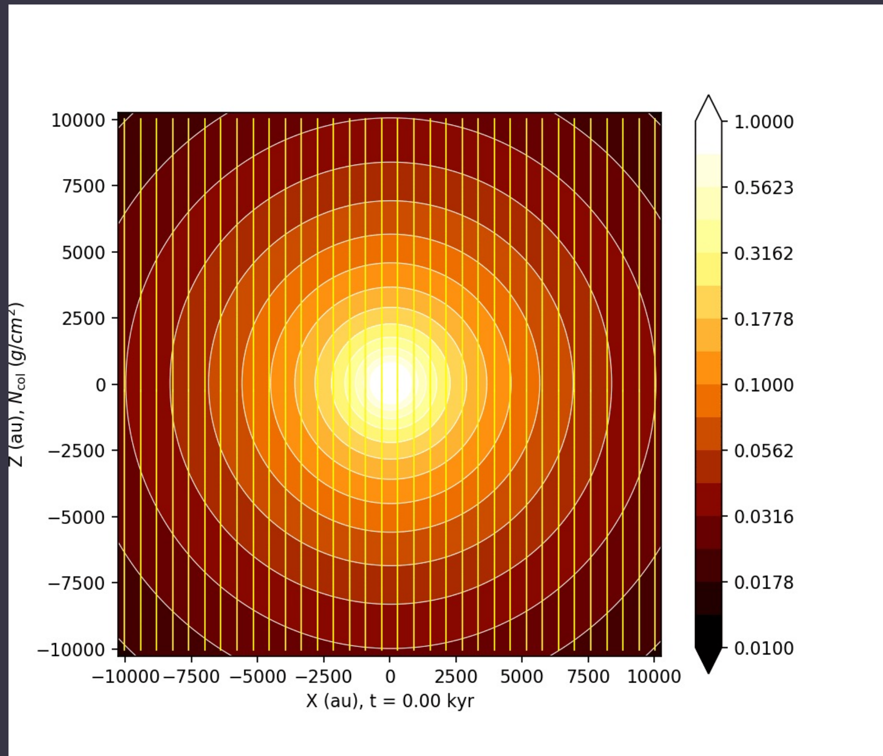
- Magnetic fields are believed to play a dynamically important role in the process of star formation, affecting fragmentation and collapse, influencing accretion and driving outflows.

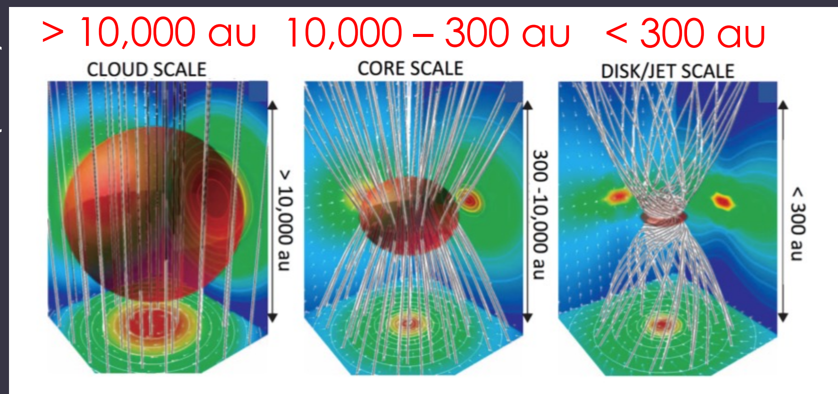
- In magnetically regulated collapse, the magnetic field is :

  i) almost uniform at cloud scales (lines not yet dragged-in)

  ii) poloidal and significantly pinched at core scales ('hourglass' morphology), as a result of collapse

  iii) and toroidal at disk scales due to rotation.

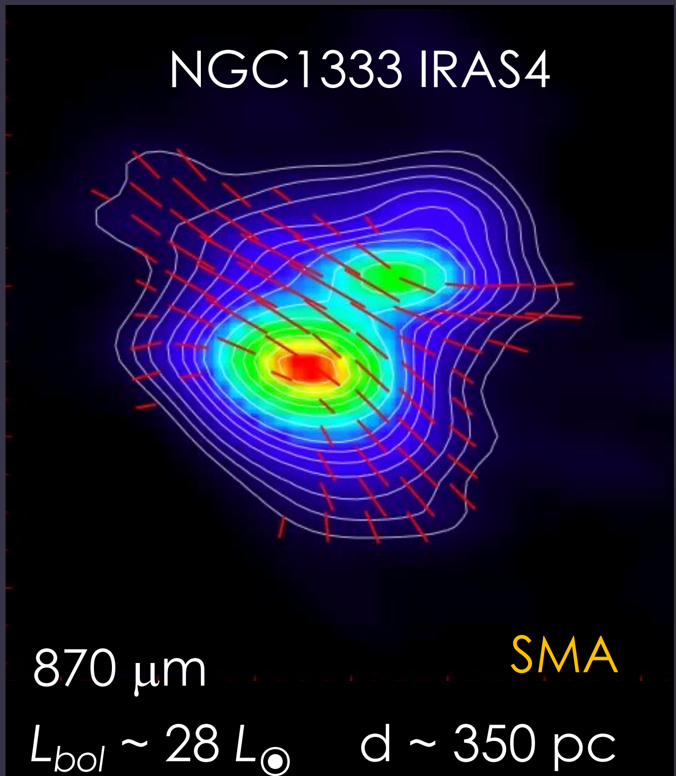




Machida et al. (2007)

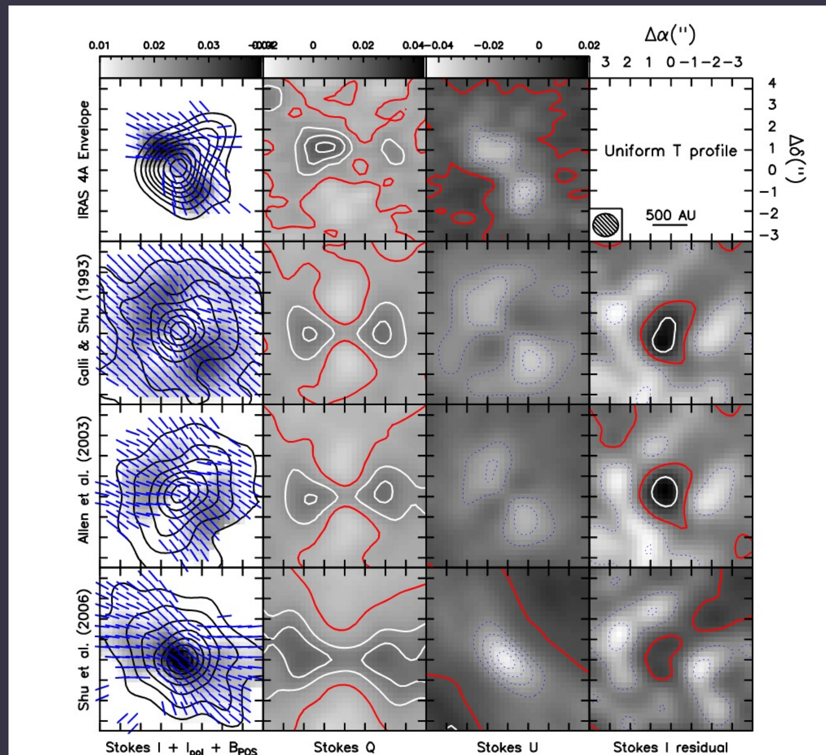
Importance of magnetic field

Low-mass star-forming regions



Girart et al. (2006, Science)

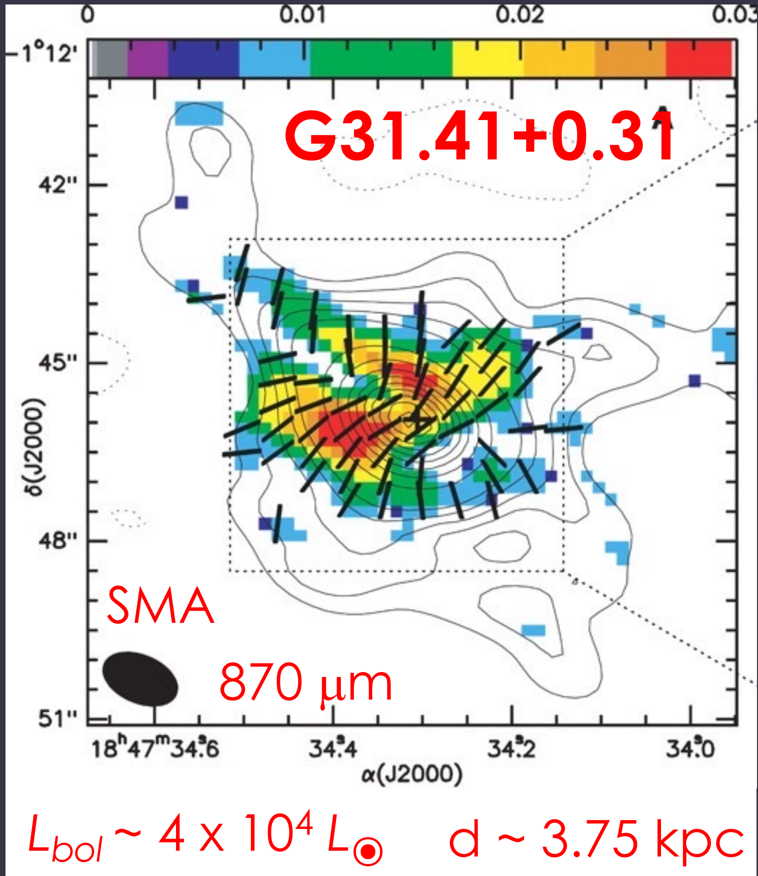
Magnetohydrodynamic collapse models



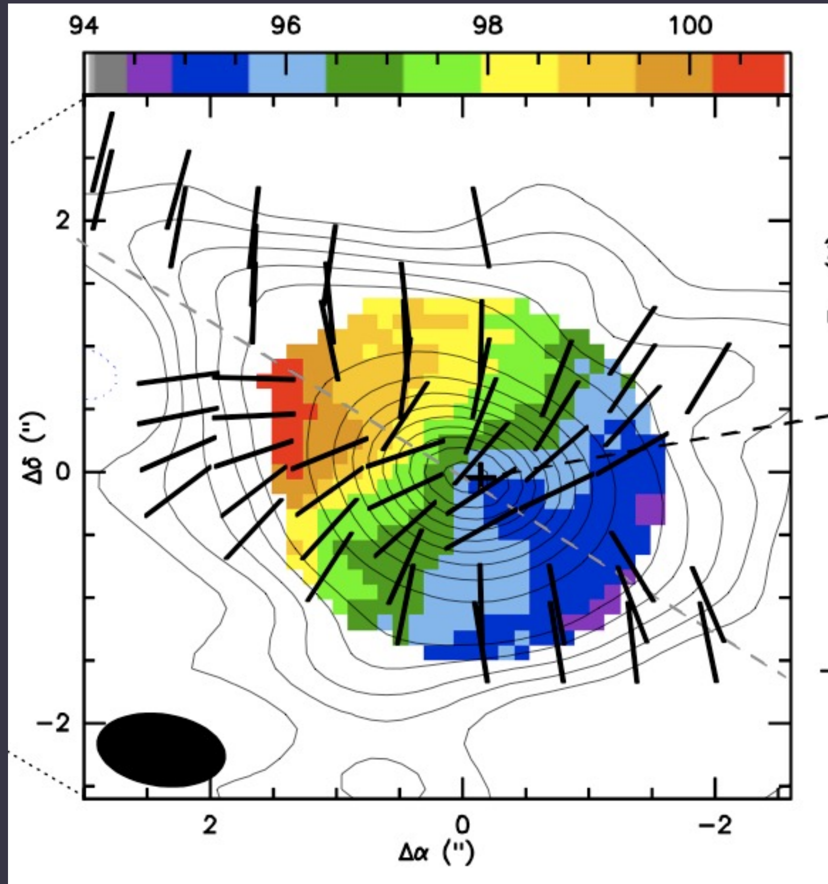
Frau, **Galli**, Girart (2011, A&A)

Importance of magnetic field

High-mass star-forming regions



Girart, **Beltrán**, et al. (2009, Science)



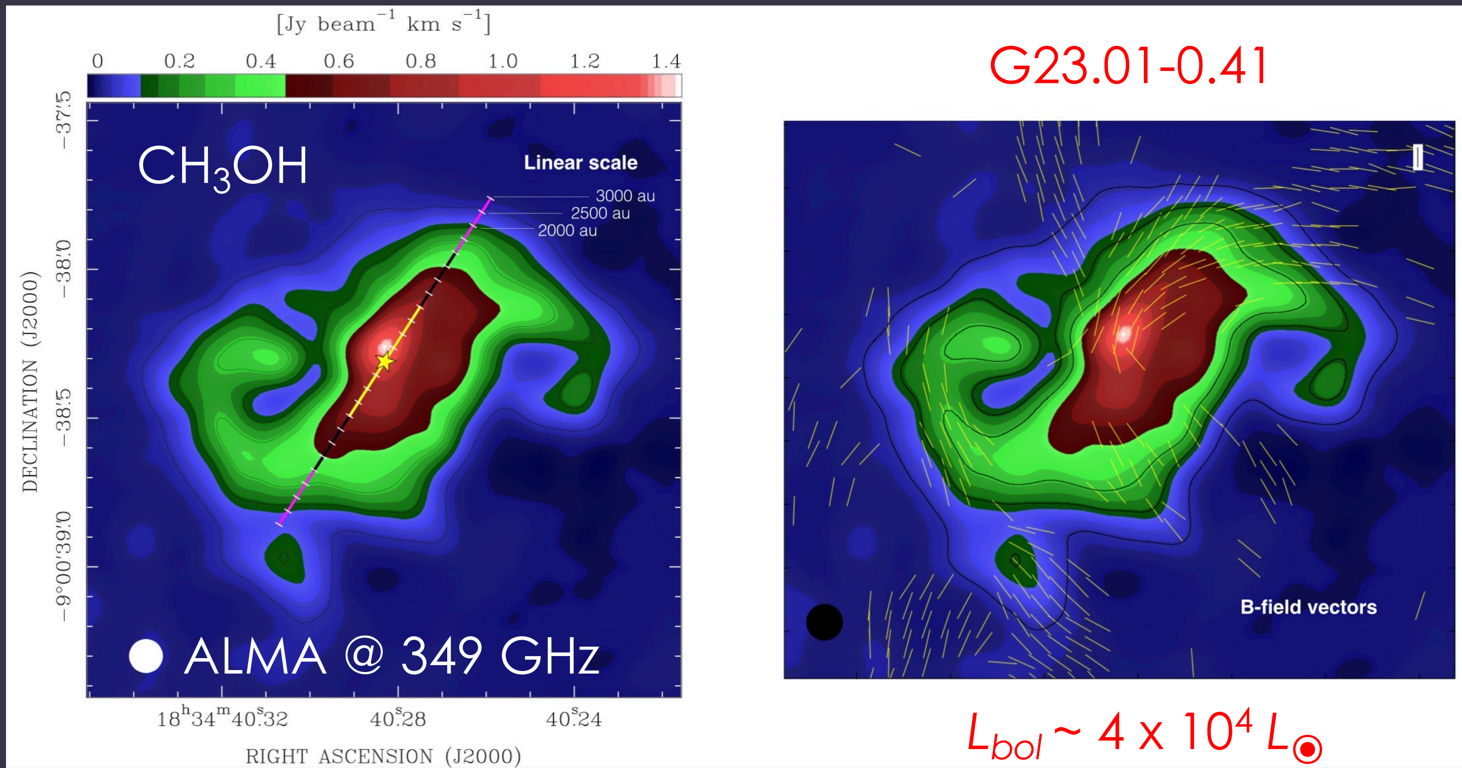
Beltrán, et al. (2004, 2005, 2018, 2022)
Cesaroni et al. (2011)

Open Questions

- Does the magnetic field play an important role in the formation of stars of all masses?
- Which is the energy balance and relative importance of the different agents controlling star formation (magnetic field, gravity, and turbulence)?
- When and how do the magnetic field and the gas decouple to allow the formation of protostellar disks?
- What is the strength and shape of the magnetic field in protostellar disks, and does it support the magnetocentrifugal launching of jets?

Tools to measure the magnetic field

- Dust polarization observations (JCMT, IRAM, ACA, ALMA, SMA)

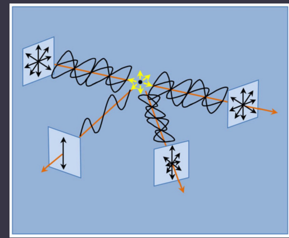


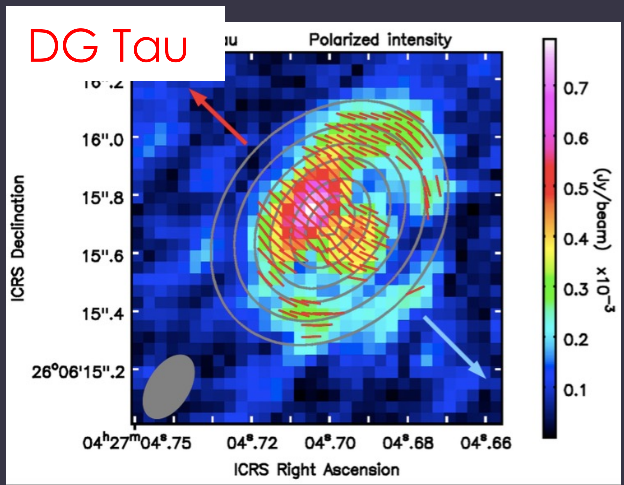
Sanna et al. (2021, A&A)

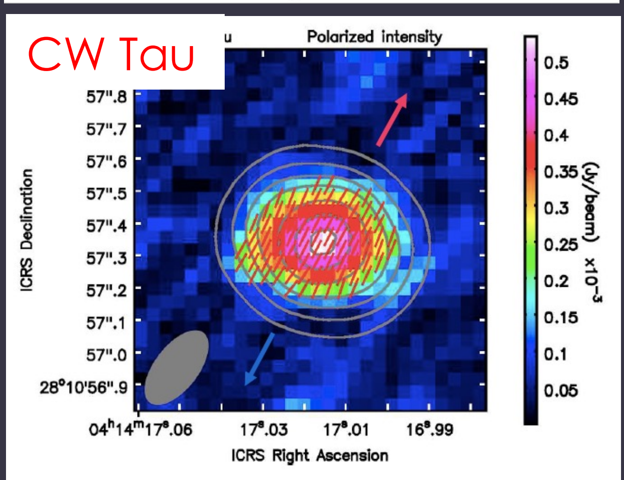
- Warped, sub-keplerian accretion disk
- B-field traces the accretion streams of the disk

Tools to measure the magnetic field

- … BUT polarization can also trace dust self-scattering







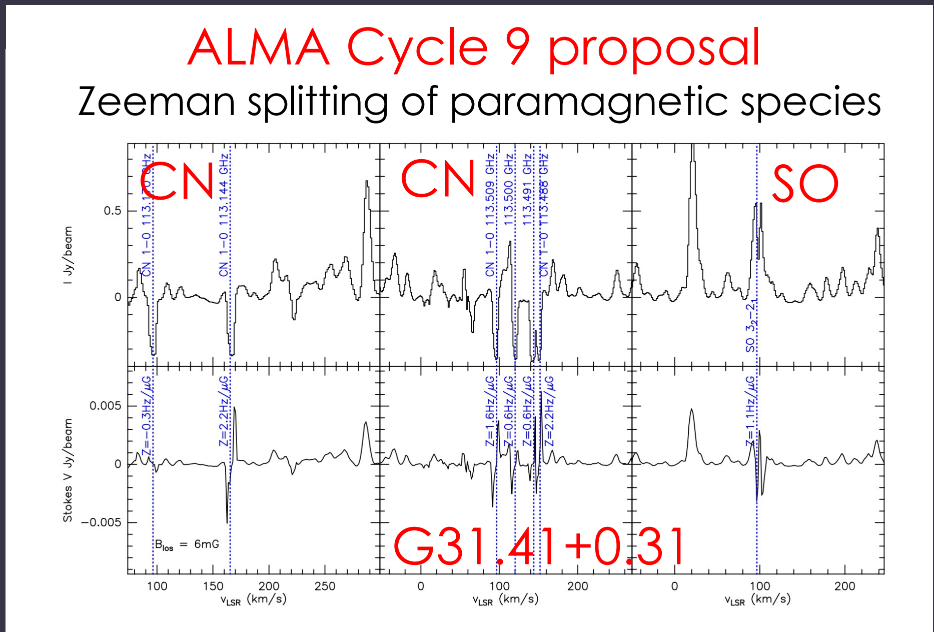
- Polarization pattern parallel to disk minor axis ALMA Band 7
- Clues on:
  - Dust settling: disk flat or flared
  - Grain size
  - ➢ Disk evolution

Bacciotti et al. (2018, ApJL)

Tools to measure the magnetic field

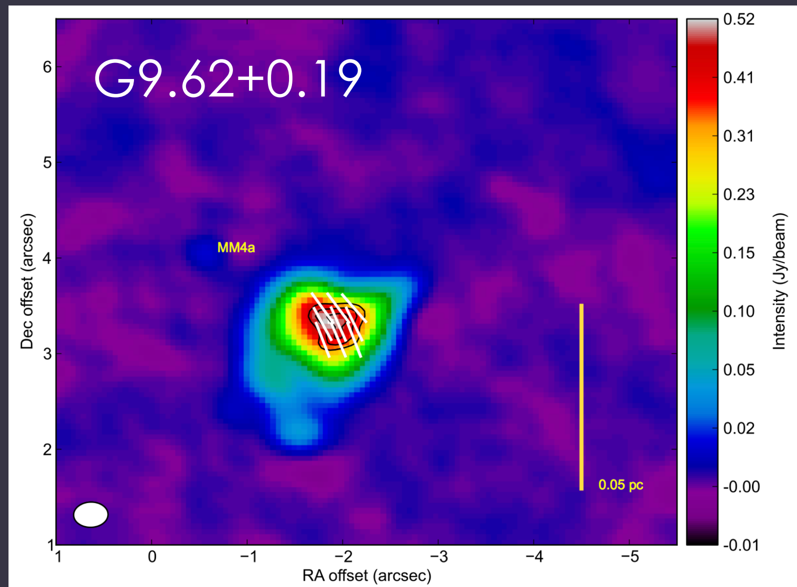
- Circular and linear polarization of thermal lines (ALMA)

Zeeman effect
(circular polarization)



- The direct way to estimate the B-field strength

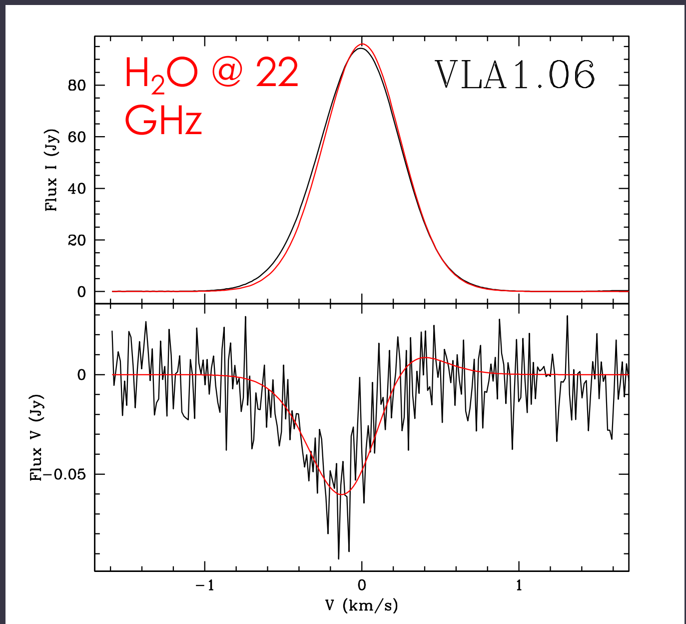
Goldreich-Kylafis effect
(linear polarization)



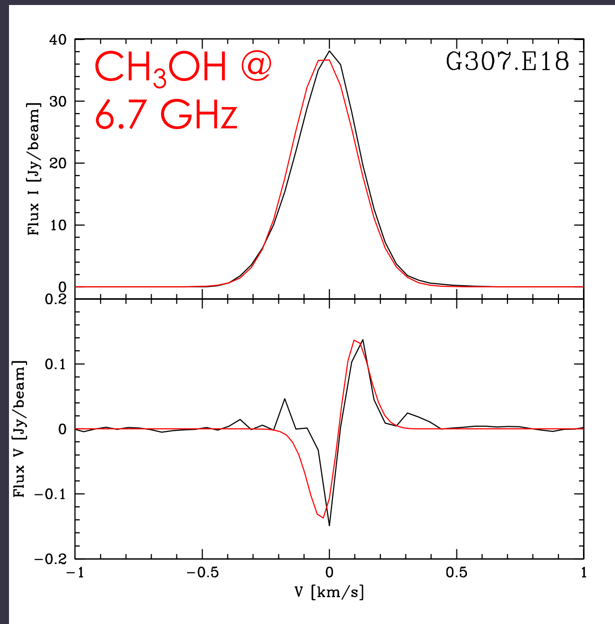
Dall'Olio et al. (2019, A&A)

Tools to measure the magnetic field

- Zeeman splitting of maser species (VLBA, EVN, VLA)

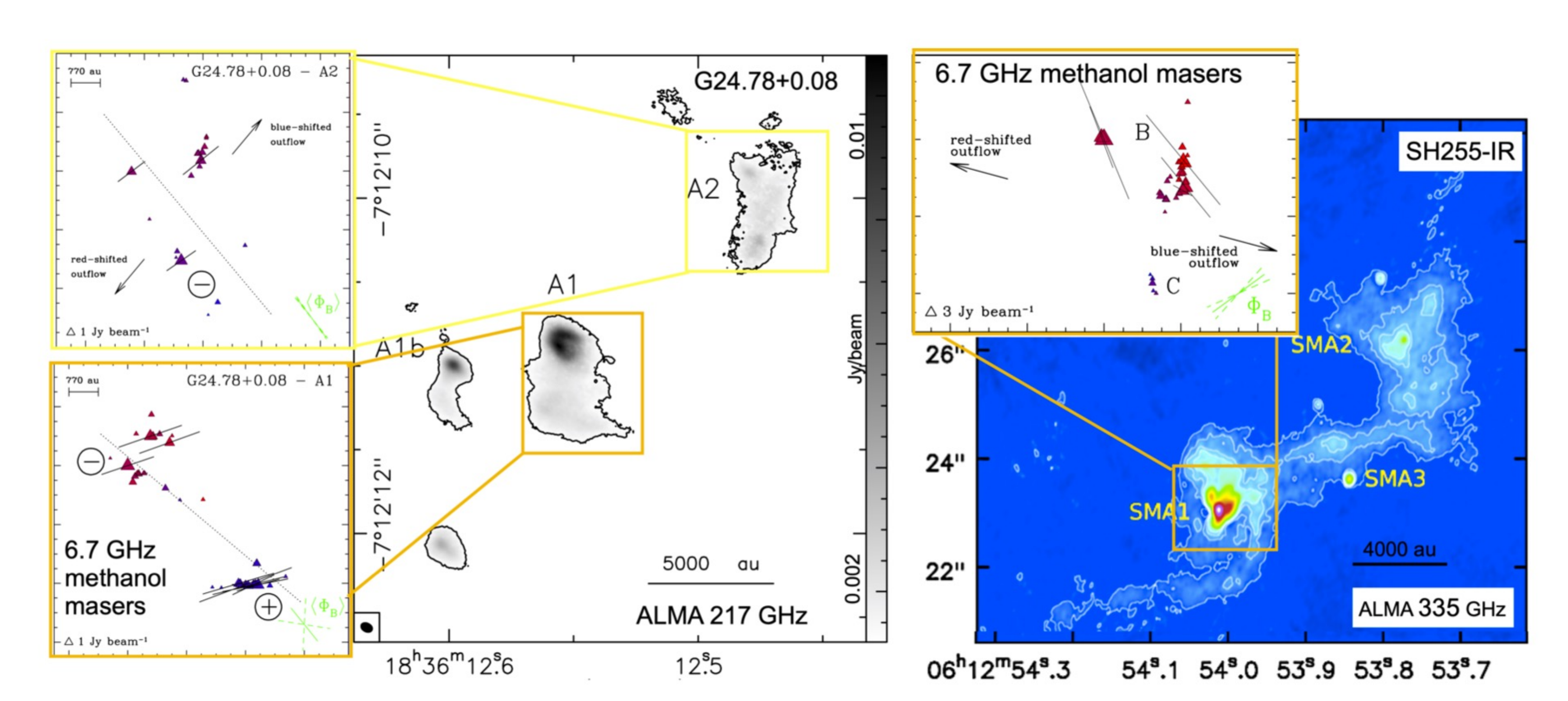


Surcis et al. (2014, A&A)



Surcis et al. (2022, A&A)

Tools to measure the magnetic field

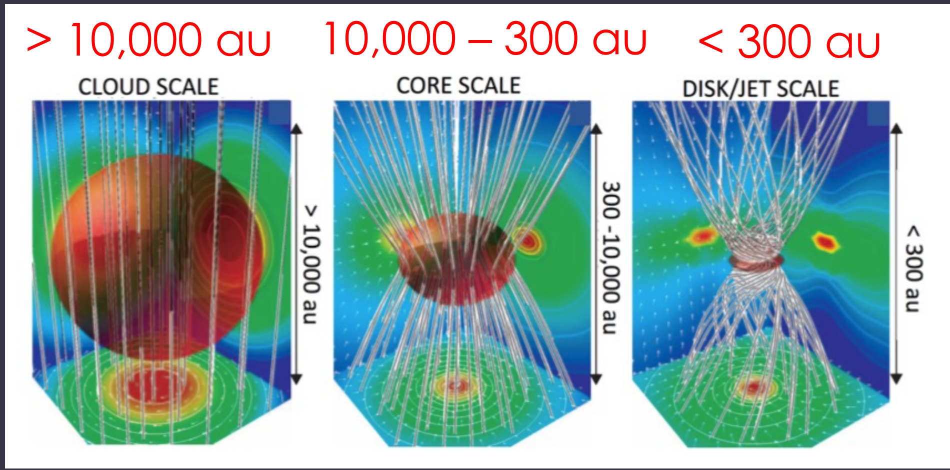


Surcis et al. (2013, A&A)
Surcis et al. (2015, A&A)

Moscadelli et al. (2021, A&A)

Programme

Machida et al. (2007)

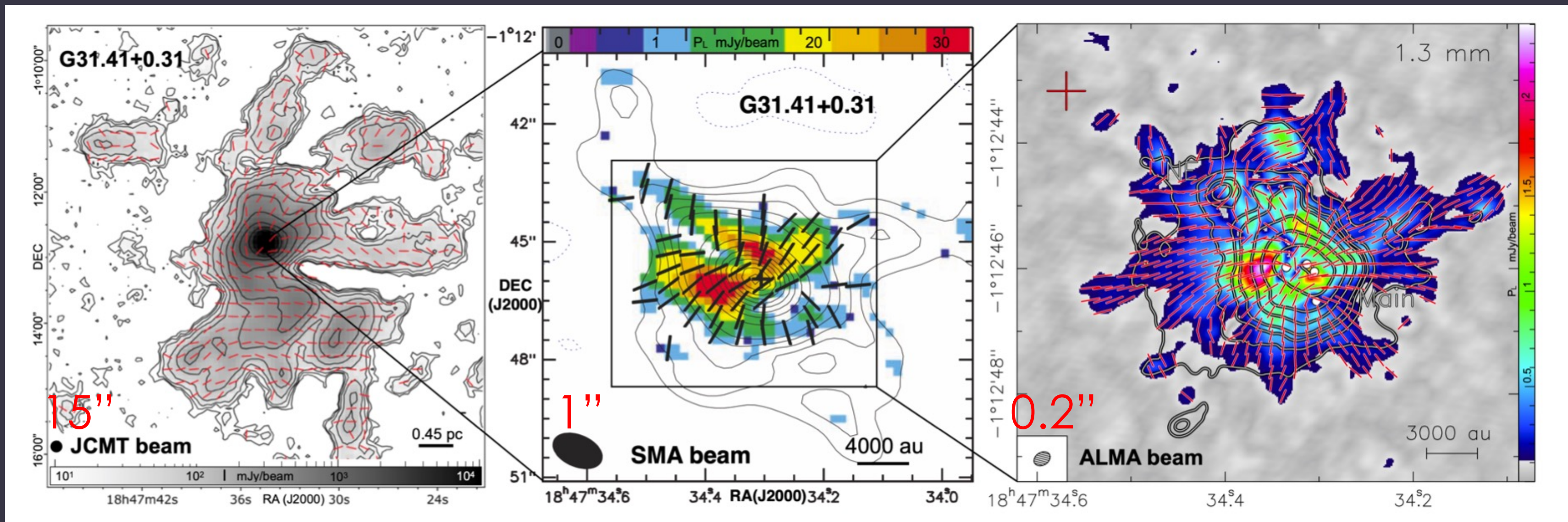


		Cloud scales (> 10,000 au)		Core scales (10,000-300 au)		Disk/jet scales scales (< 300 au)				
Source	Luminosity and distance	Thermal emission		Thermal emission		Thermal emission		Maser emission		
		Kinematics	B morph.	Kinematics	B morph.	Kinematics	B morph.	Kinematics	B morph.	B strength
G35.20-0.74	$1.6 \times 10^{3} L_{\odot}$ 2.2 kpc	✓	⌛	✓	✓	✓	●	●	✓	✓
Sh 2-255 IR	$9.0 \times 10^{3} L_{\odot}$ 2.3 kpc	✓	⌛	✓	⌛	✓	●	✓	✓	✓
G16.59-0.05	$1.3 \times 10^{4} L_{\odot}$ 2.3 kpc	✓	⌛	✓	✓	✓	●	✓	✓	✓
IRAS 18089-1732	$1.3 \times 10^{4} L_{\odot}$ 3.6 kpc	✓	⌛	✓	✓	✓	✓	●	✓	✓
G29.95-0.02	$1.8 \times 10^{4} L_{\odot}$ 5.3 kpc	✓	⌛	✓	✓	✓	●	●	✓	✓
G35.02+0.35	$2.8 \times 10^{4} L_{\odot}$ 3.4 kpc	✓	⌛	✓	✓	✓	●	✓	✓	✓
G24.78+0.08	$4.0 \times 10^{4} L_{\odot}$ 6.7 kpc	✓	⌛	✓	⌛	✓	●	✓	✓	✓
G31.41+0.31	$4.4 \times 10^{4} L_{\odot}$ 3.7 kpc	✓	✓	✓	✓	✓	✓	✓	●	●
G23.01-0.41	$1.0 \times 10^{5} L_{\odot}$ 5.6 kpc	✓	⌛	✓	✓	✓	✓	✓	✓	✓

Table 1. The sources of our sample: the tool adopted to study the magnetic field at the different scales (thermal emission or maser emission). The symbols indicate which data are already available (✓), which proposals have been submitted (⌛), or will be submitted soon (●).

Example: G31.41+0.31

Cloud scale — Core scale — Core to disk scale



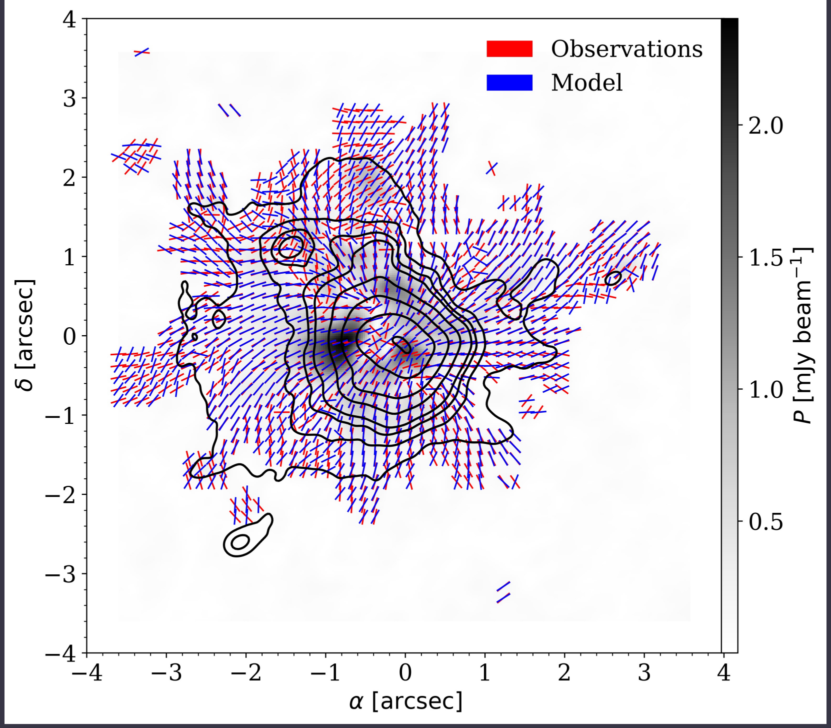
Girart, **Beltrán**, et al. (2009, Science)
Beltrán, **Padovani**, et al. (2019, A&A)

- Orientation and morphology of B-field
- Strength in the plane of sky (DCF method)
- Relative magnitudes of the mean and turbulent components of the field.

Example: G31.41+0.31

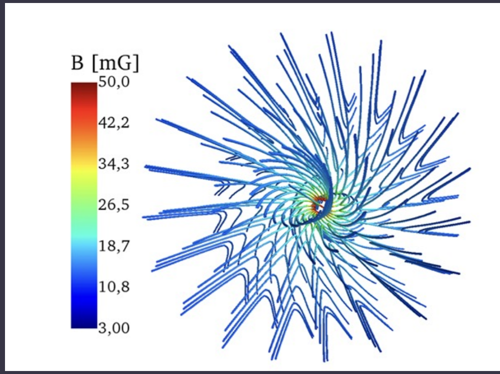
- We used the *DustPol* module of the ARTIST package (**Padovani** et al. 2012) to model the B-field morphology (Stokes I, Q, and U).

- The best fit model suggests that the magnetic field associated with the Main core in G31 is well represented by a purely poloidal field, with a small toroidal component of the order of 10% of the poloidal component oriented SE-NW and inclined.

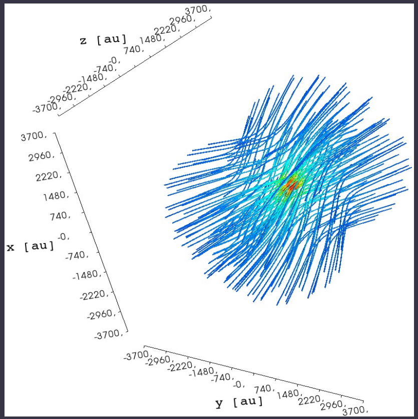


Beltrán, **Padovani** et al. (2019, A&A)

Padovani et al. (2013, A&A)



pole-on view



edge-on view

Projects: present and future

- VLA observations of CH_3OH masers at 44 GHz ✓
- ALMA and SMA dust pol. of ALMAGAL cores ✓
- SMA and ALMA dust pol. observations at core scales ⌛
- ALMA dust pol. observations at cloud scales ⌛
- ALMA circular polarization CN and SO: Zeeman effect ⌛
- ALMA linear polarization CO and SiO Goldreich-Kylafis effect ⌛

- IRAM NIKA-2 polarization camera
- AtLAST telescope (next generation 50-m telescope): leading the AtLAST Science Use case: "A survey of the dust polarised thermal emission from the Galactic Plane"

PHISM: *Physics of the Interstellar Medium*

TEAM:

- **Daniele Galli** (INAF-OAA): magnetic fields, gravitational collapse
- Francesca Bacciotti (INAF-OAA): MHD winds, jets, polarization
- Maite Beltrán (INAF-OAA): star forming regions, polarization, ALMA
- Riccardo Cesaroni (INAF-OAA): protostellar disks, ALMA
- Francesco Fontani (INAF-OAA): star forming regions, astrochemistry
- Luca Moscadelli (INAF-OAA): masers and magnetic fields
- Marco Padovani (INAF-OAA): cosmic-ray acceleration and propagation

GOALS:

- To foster the collaboration between participants belonging to this area of research within INAF and with their international collaborators
- To train new researchers through the organization of schools, teaching graduate/PhD courses.

CASTOR: *Cosmic rAys and STar fORmation*

TEAM:

- **Marco Padovani** (INAF-OAA): cosmic-ray acceleration and propagation
- Francesca Bacciotti (INAF-OAA): MHD winds, jets, polarization
- Maite Beltrán (INAF-OAA): star forming regions, polarization, ALMA
- Daniele Galli (INAF-OAA): magnetic fields, gravitational collapse

GOALS:

- To study the effects of low-energy CRs in star-forming regions: ionization and chemistry of circumstellar discs, non-thermal and gamma-ray emission in protostars and in HII regions.
- To make predictions for future observations with SKA, CTA, E-LOFAR, JWST, and ngVLA.

Leadership

- Unique group combining all types of polarization observations (from maser to dust) in star-forming regions at all scales + theory and simulations
- Leaders on maser polarization observations
- Leaders on calibration of ALMA polarization observations (non-standard observing mode)
- World experts on study of theory of magnetic fields and CRs in SF regions

Funds

- Indirect funds from the Swedish Research Council: Daria Dall'Olio (VR fellowship working at Arcetri)

- Submitted: Large Project MAGMA

Critical aspects

- Funding
- Manpower: Postdocs and PhD students
- Need to increase expertise at INAF: in 5 years many retirements
- Lack of numerical skills for hydrodynamics and magnetohydrodynamics applied to the ISM, including microphysical aspects related to computational astrochemistry

Critical aspects

- Funding
- Manpower: Postdocs and PhD students
- Need to increase expertise at INAF → Cosmic rays: the salt of the star formation recipe conferences;

  Schools, courses or PhDs on polarization

- Lack of numerical skills for hydrodynamics and magnetohydrodynamics applied to the ISM, including microphysical aspects related to computational astrochemistry → a school has been organized on the topic (Arcetri-KROME School 2016) and we present these topics in a course at Unifi for the master's degree