Stellar and planetary formation in the Galaxy: from molecular clouds to protoplanetary disks

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Rome
&
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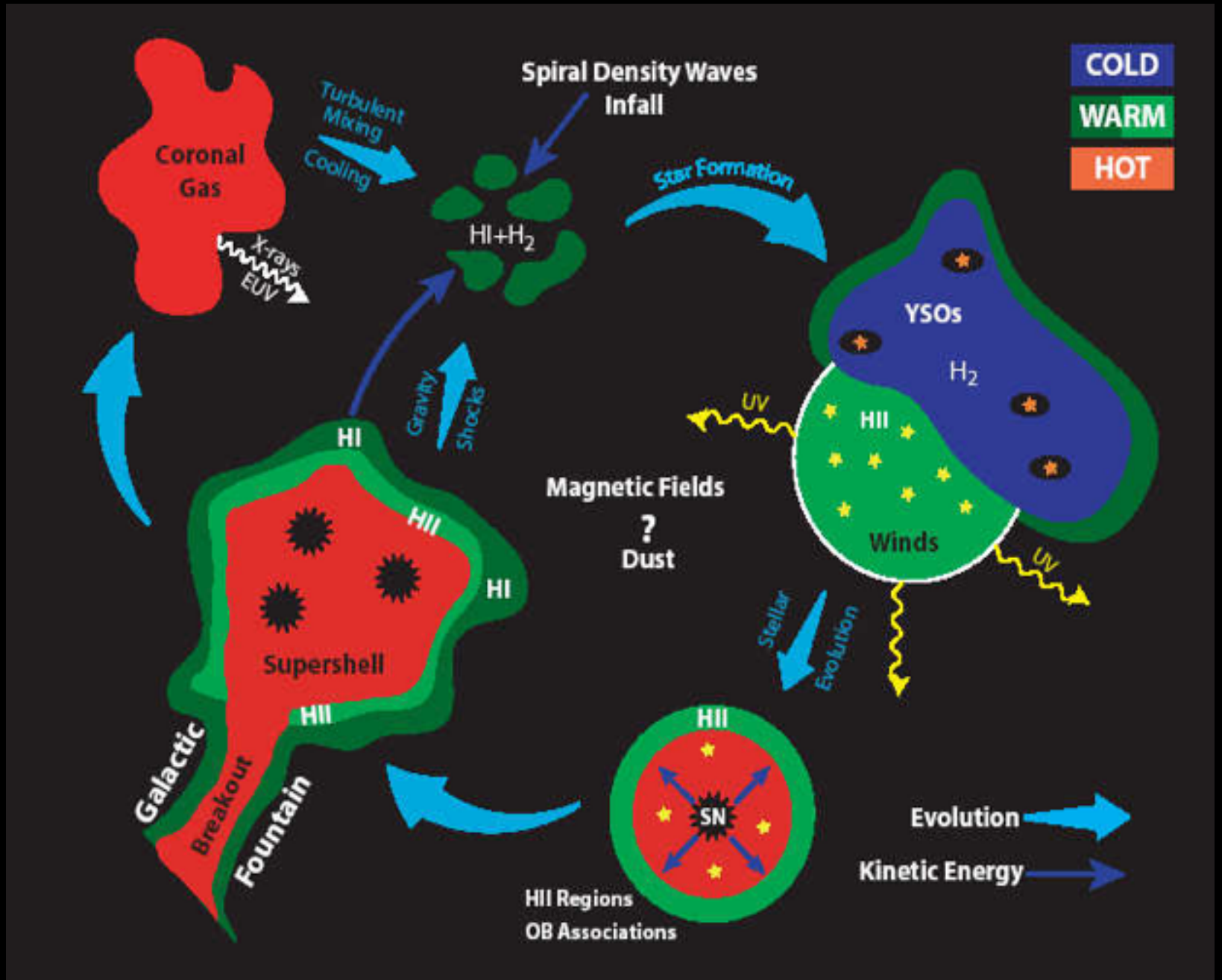
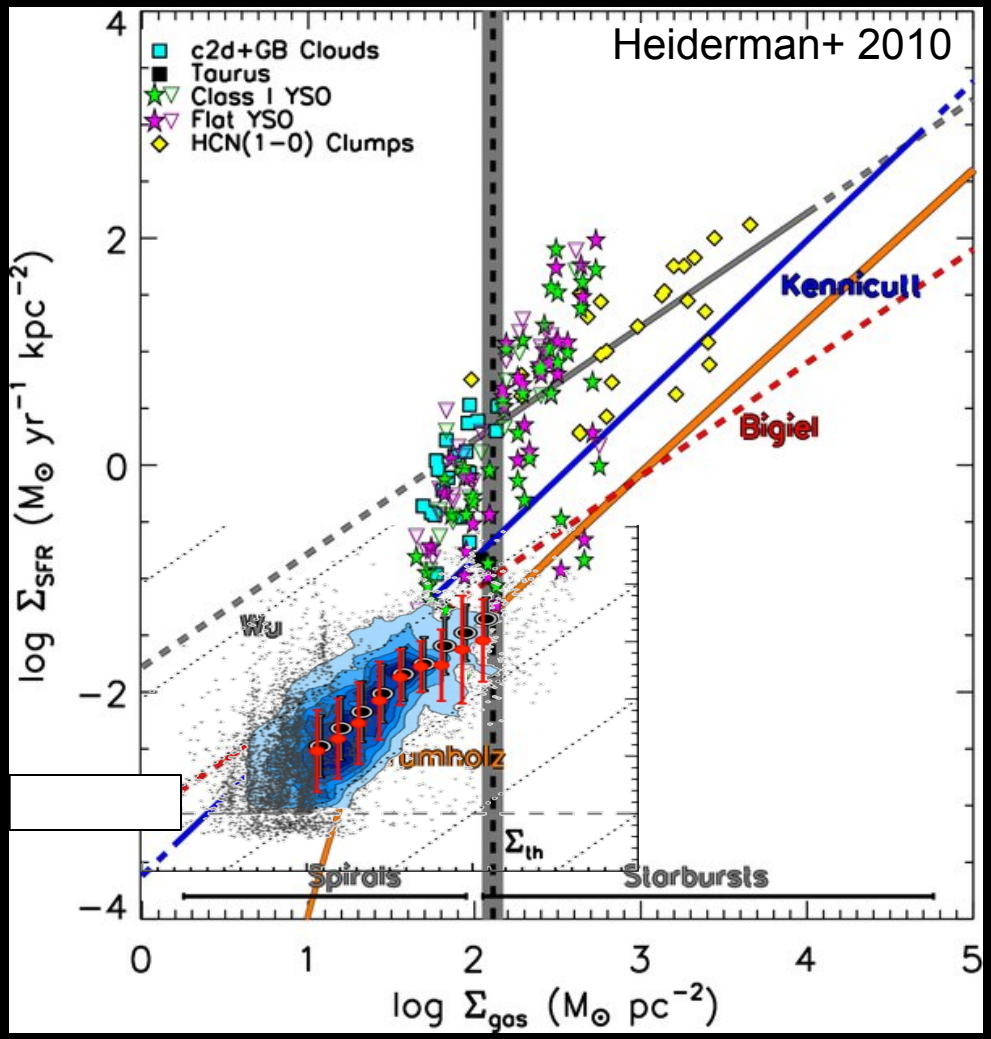
INAF, CSN2 May 19 2021

Dust & gas as tracers of the Galactic Ecology



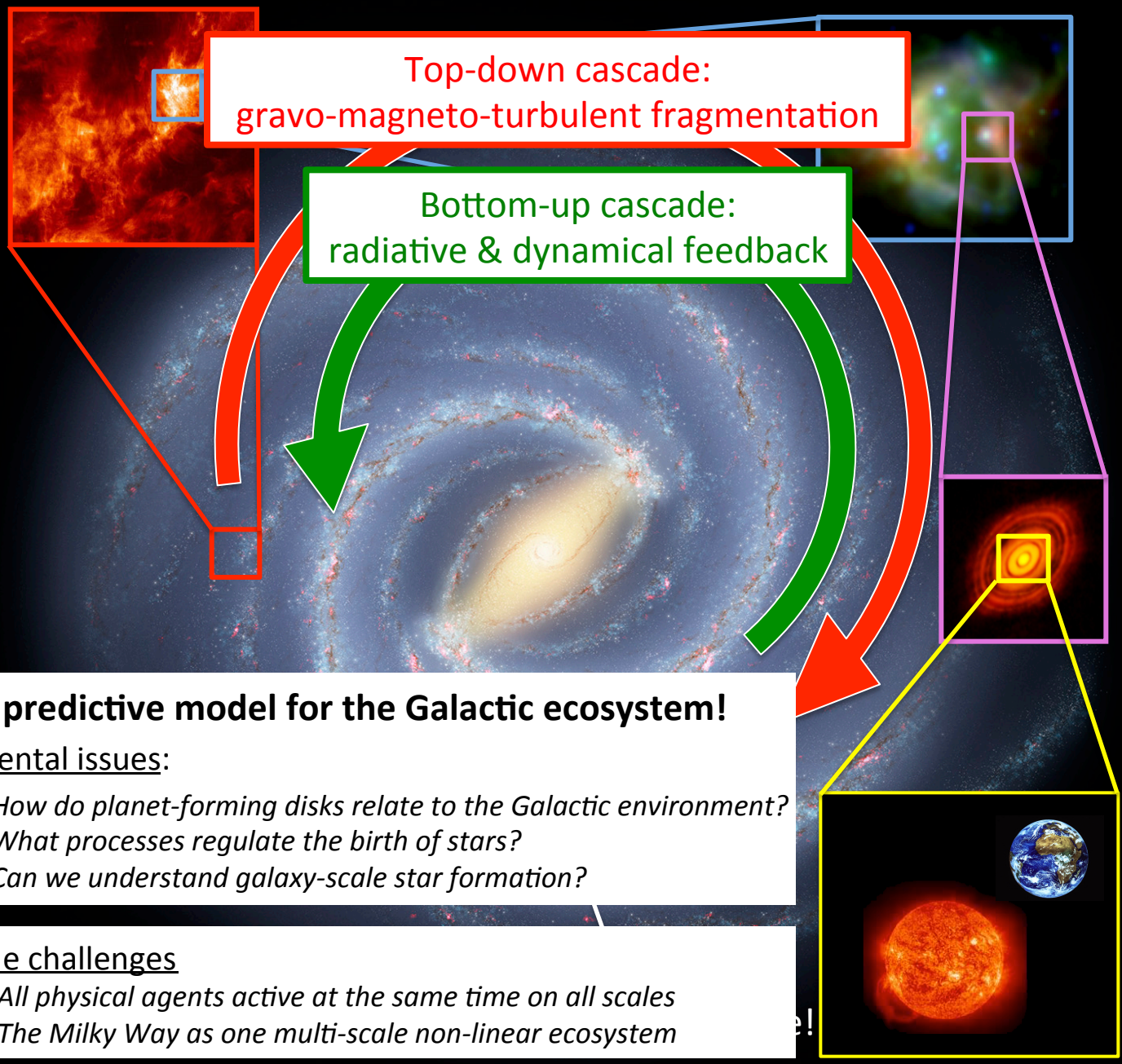
Basic Rationale for star-formation-driven large Galactic Surveys



Aim: Identify the critical parameters that govern the formation and evolution of dense cluster-forming clumps within the diversity of environmental conditions:

- Spontaneous/triggered SF ?
- Star Formation on/off Filaments ?
- Depending on the position in the Galaxy
- w.r.t. Spiral Arms
- etc.

understand if & how the mix of the ingredients conspire to determine a global Star Formation law



The first predictive model for the Galactic ecosystem!

Three fundamental issues:

PLANETS → *How do planet-forming disks relate to the Galactic environment?*
STARS → *What processes regulate the birth of stars?*
GALAXY → *Can we understand galaxy-scale star formation?*

The challenges

✓ *All physical agents active at the same time on all scales*
✓ *The Milky Way as one multi-scale non-linear ecosystem*

Realistic illustration of Milky Way (NASA/JPL-Caltech)

Historical perspective

ISO
3→200μm

→ 1998

- LWS Instrument contribution: DPU+OBS+Instrument Team
- GT Programs: YSOs, PDRs, Shocks

Herschel
70→500μm

1999-2009-2013

- PACS/SPIRE/HIFI Instrument contribution: DPU+OBS+Instrument Teams
- Co-PI: Gould Belt Survey (dust mapping in nearby SFRs)
- Co-I: HOBYS (continuum mapping in nearby massive SFRs), WISH (Water in SFRs), CHESS (YSOs spectral mapping)
- **PI (SM): Hi-GAL Herschel infrared Galactic Plane Survey (largest Herschel Open Time Key-Project, and only one with Italian PI)**
  → *2 ASI contracts, total ~**1M€** [Univ. Roma1-2, OAA, OACT]*

SEVENTH FRAMEWORK PROGRAMME

2013-2016 "VIALACTEA: the Milky Way as a star formation engine" (PI: SM), Coll. FP7-SPACE-2013-1 → **2.5M€** (1M€ in Italy: IAPS, OACT, OATS, OACN)

erc European Research Council

2020-2026 "ECOGAL: Understanding our Galactic ecosystem" (PI: SM), ERC-SYNERGY→ **2.5M€** (**all** in Italy).

Molinari et al. 2016

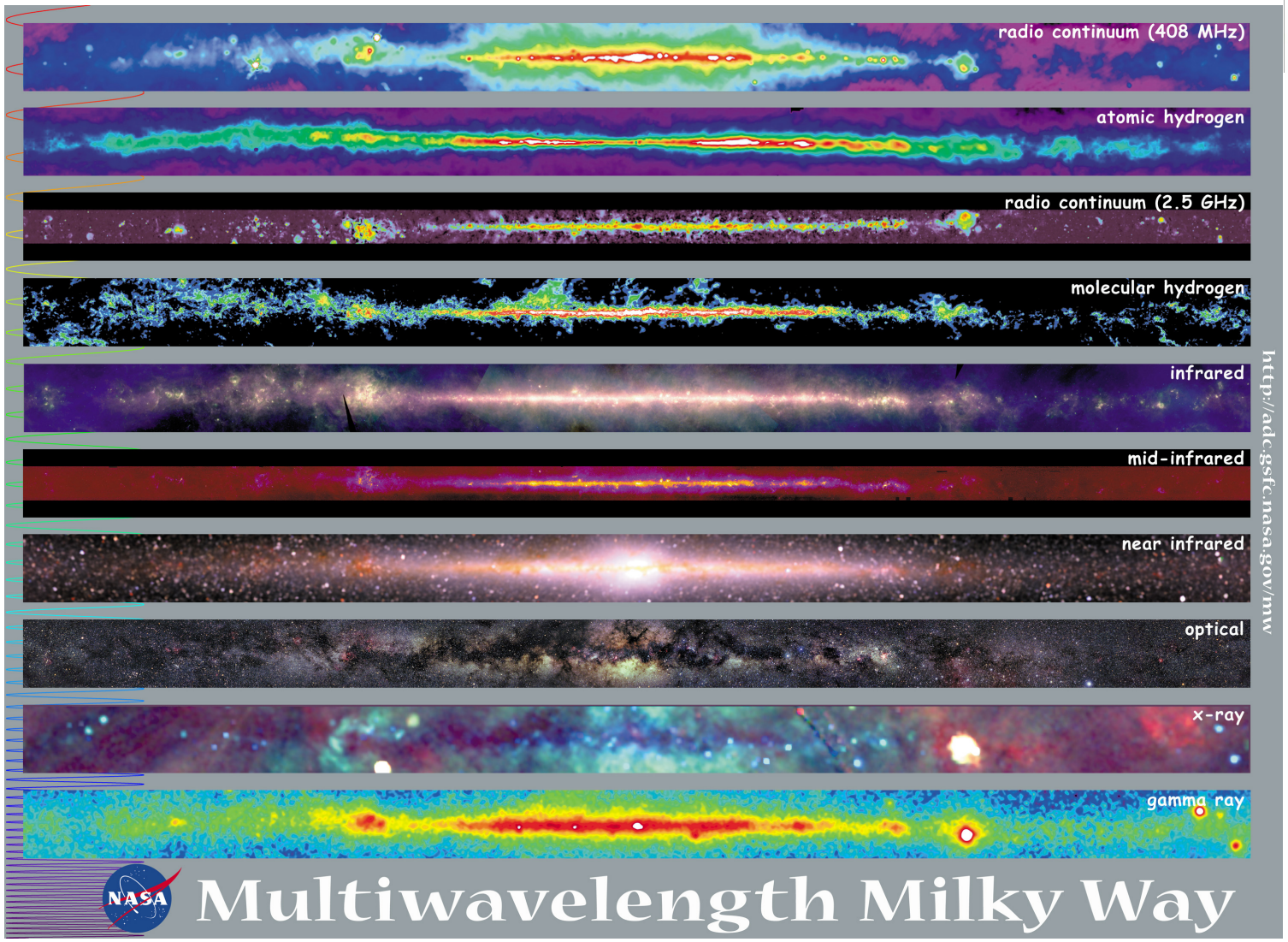
Hi-GAL

the Herschel infrared Galactic Plane Survey

70-160-250μm composite

- We are an end-to-end group with a wide range of technological, software and scientific expertise
- Astronomers work in close contact with engineers and technicians in building the scientific instruments
- Development of optimized algorithms for an image processing pipeline: ROMAGAL (Traficante et al. 2011), UNIMAP (Piazzo et al. 2015)
- Development of optimised algorithms for automatic source extraction and photometry: CuTEx (Molinari et al. 2011)
- We develop novel approaches for the morphological analysis of the extended emission in the interstellar medium: e.g, automatic filament extraction (Schisano et al. 2014, 2020).

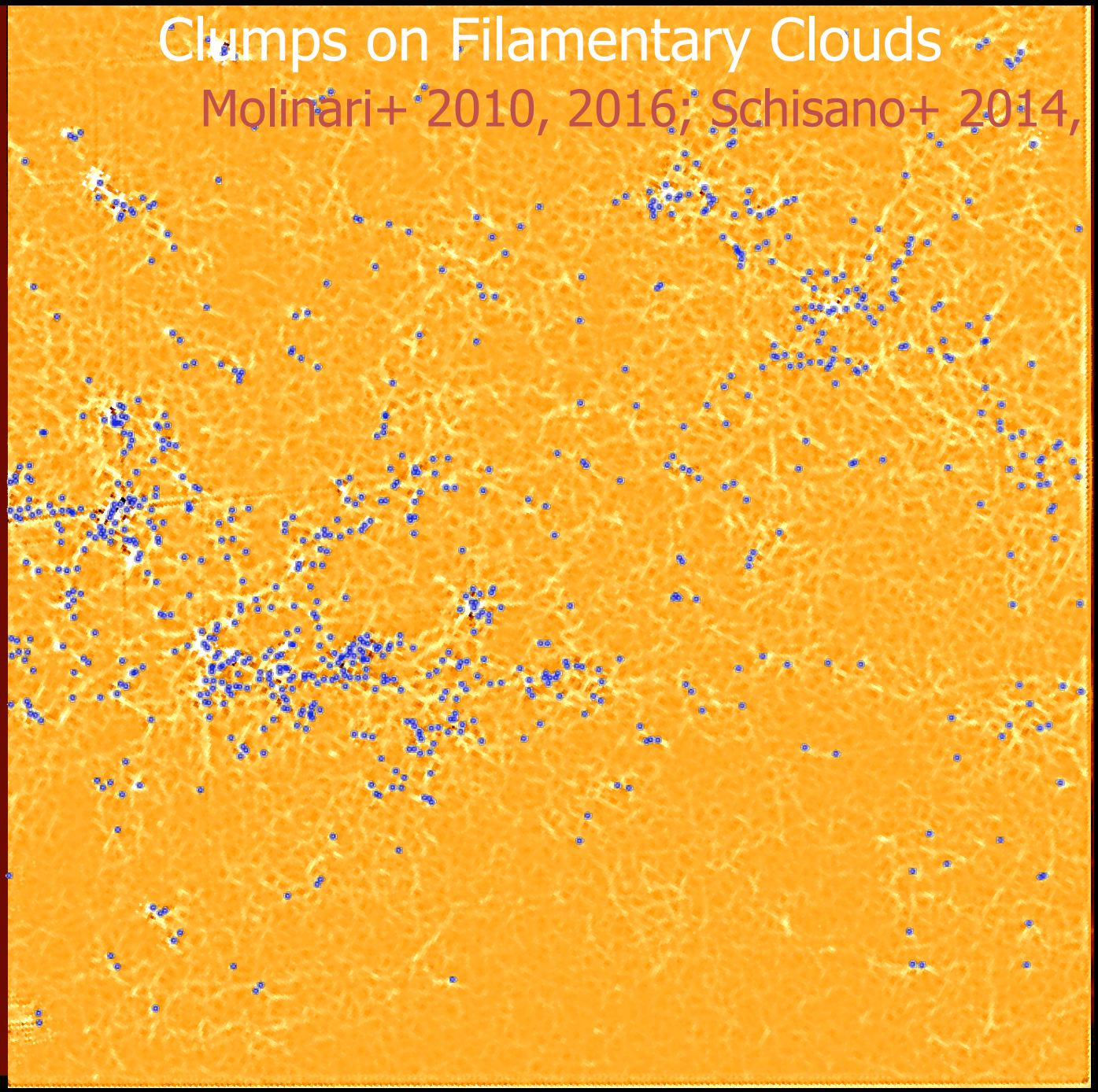
We write the science papers !!



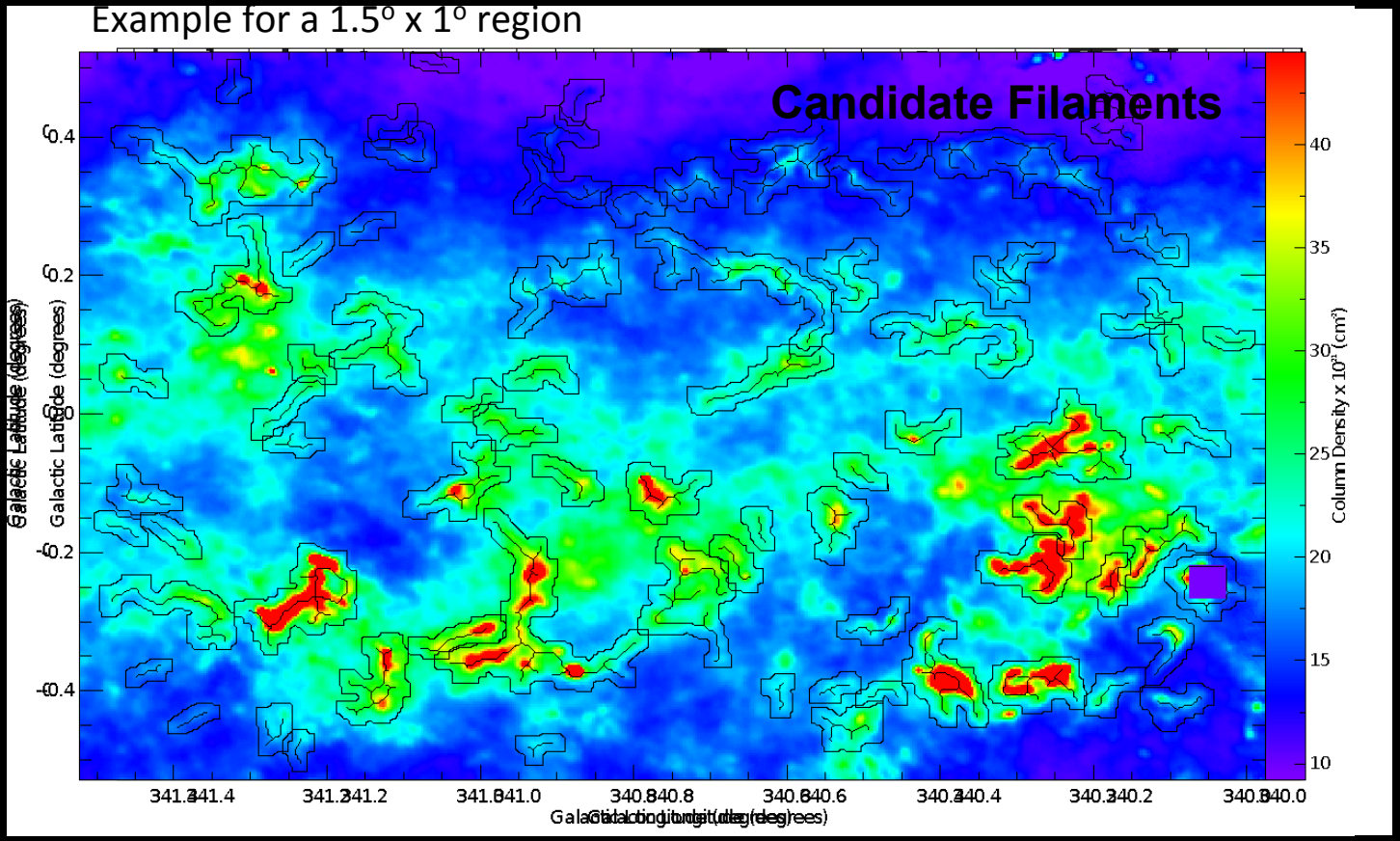
SEVENTH FRAMEWORK PROGRAMME

Clumps on Filamentary Clouds

Molinari+ 2010, 2016; Schisano+ 2014, 2019



The filamentary Milky Way



Schisano et al. 2014

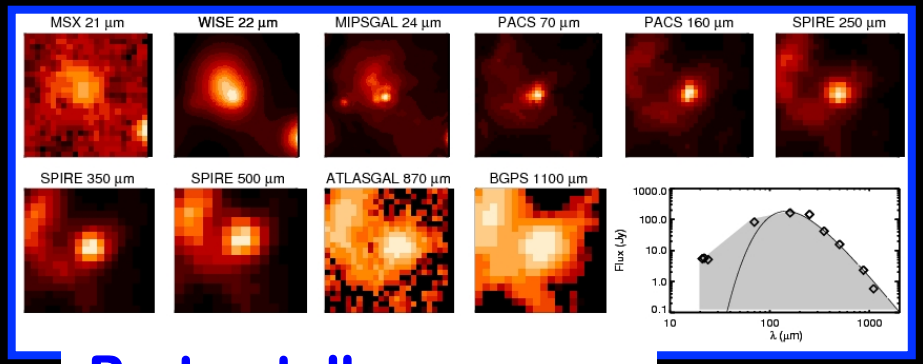
KEY SHAPE PARAMETERS:

-) elongated
-) extended
-) contrasted

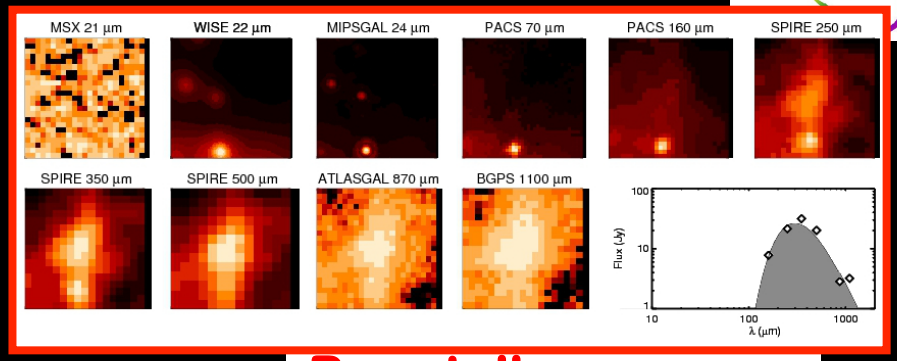
Tool applied to the entire dataset of Hi-GAL data building up an extensive catalogue of candidate filaments

The catalogue contains both **single isolated linear filaments** and large complex networks: a total of **32245** **candidates** in the Galactic Plane (Schisano+ 2019)

Compact sources on the Galactic Plane

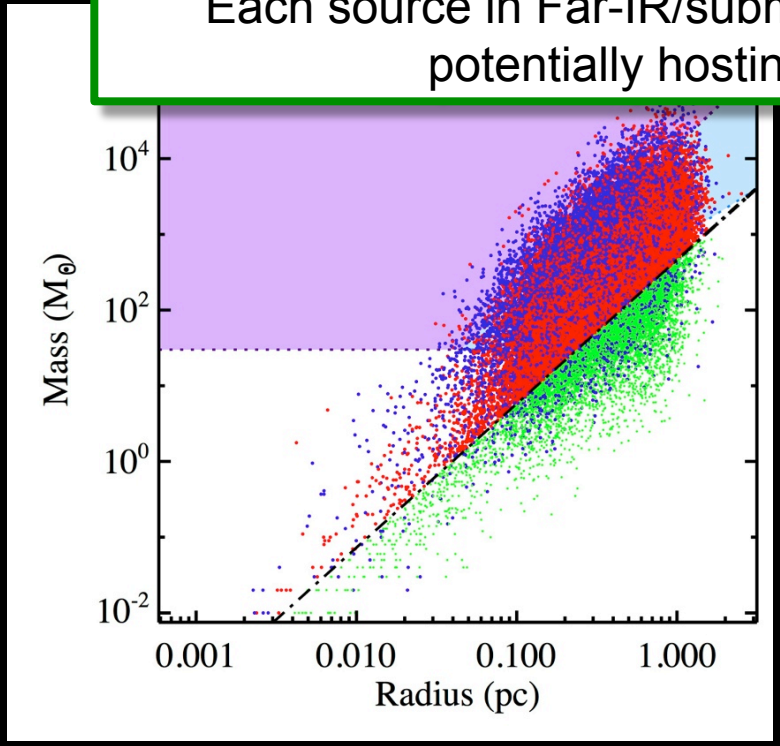


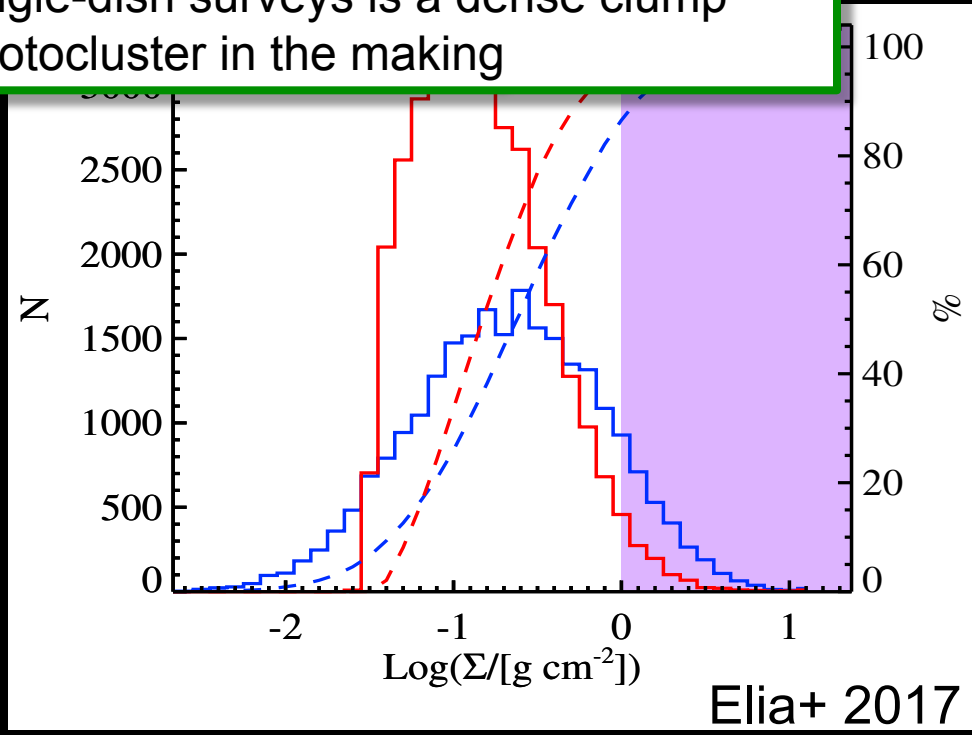
Proto-stellar sources



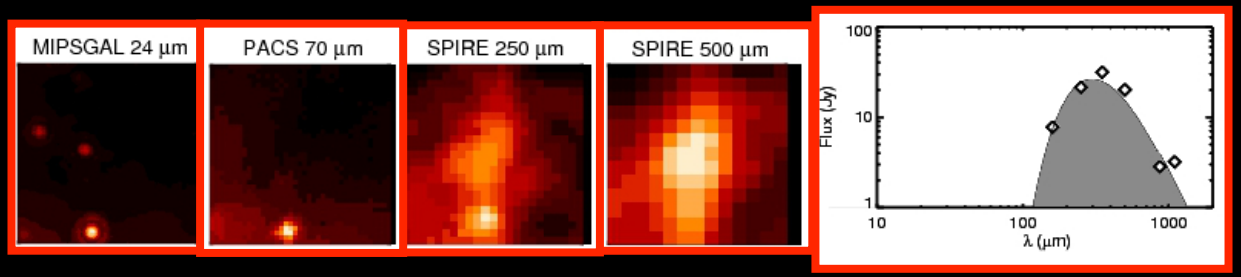
Pre-stellar sources

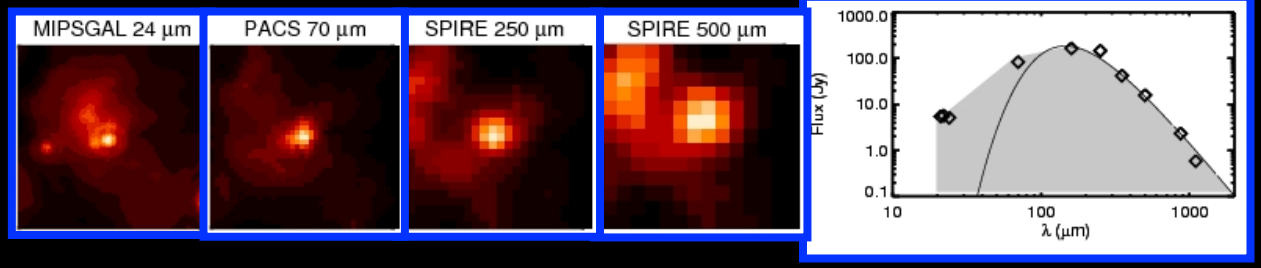
Nearly 150,000 compact clumps revealed (Elia+ 2017, 2021)
Each source in Far-IR/submm single-dish surveys is a dense clump potentially hosting a protocluster in the making

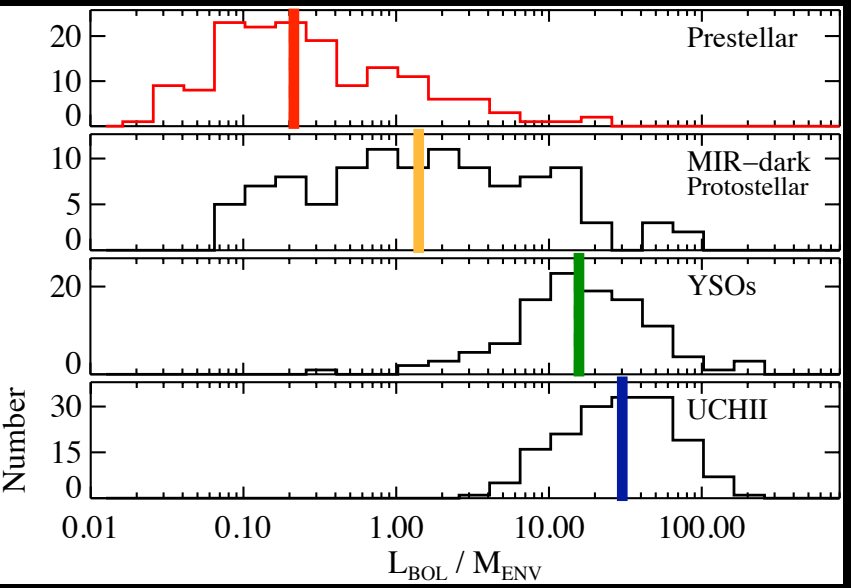


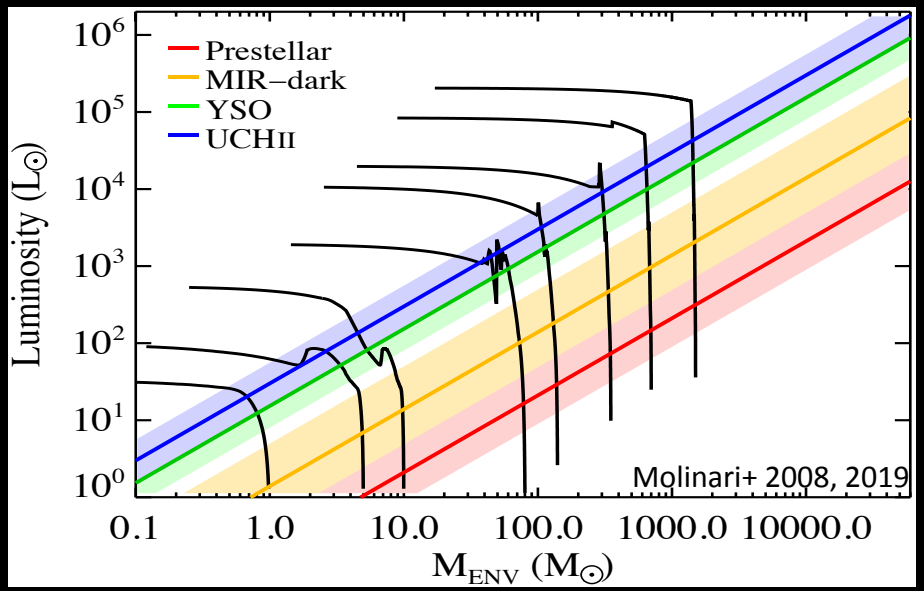


Tracing the evolution

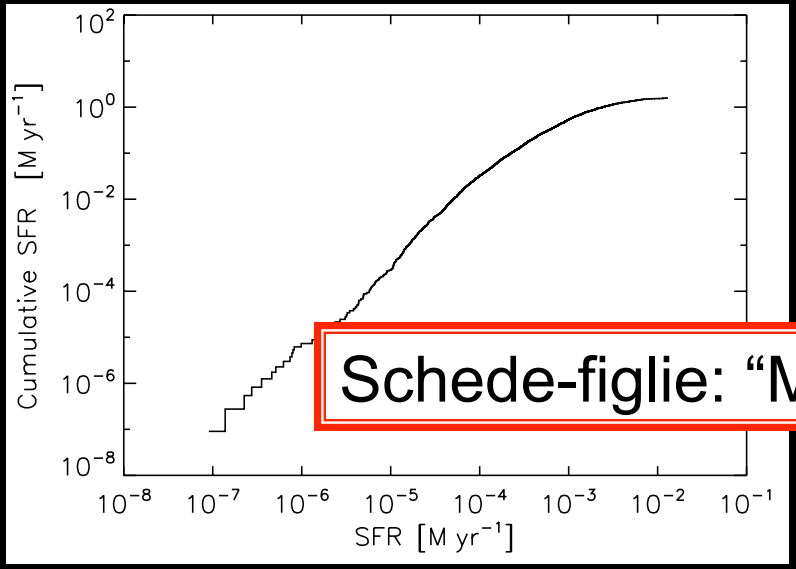








The Milky Way Map of the Star Formation Rate

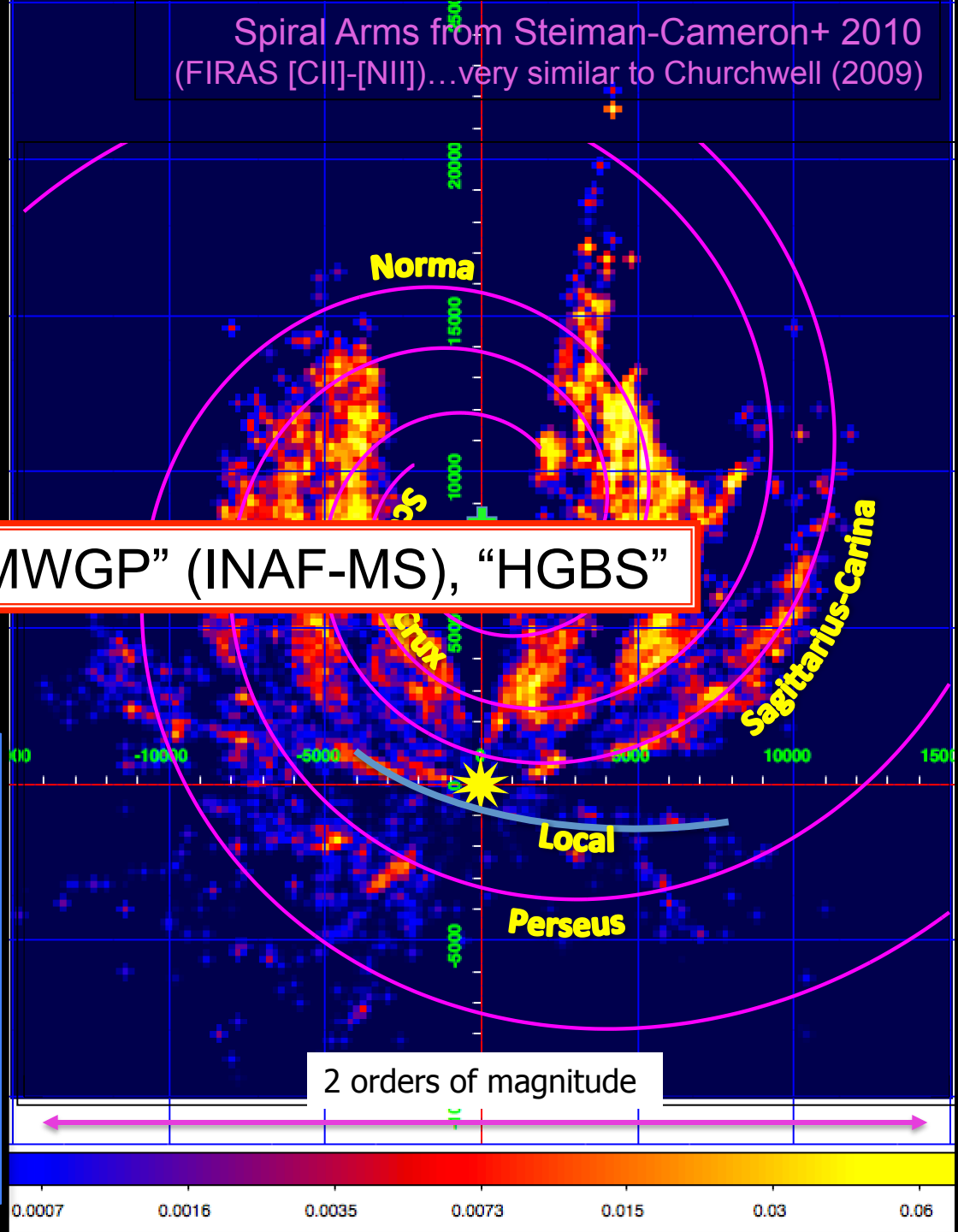


- Cumulative distribution yields an integrated SFR ≈ 1.6 $M_{\odot}yr^{-1}$
- 20% of the cells are contributing 65% of the total SFR
- The +15°≥ *l* ≥ -10° adds ≈ 0.57 $M_{\odot}yr^{-1}$ assuming all clumps at D=8400pc

Elia+ in prep.

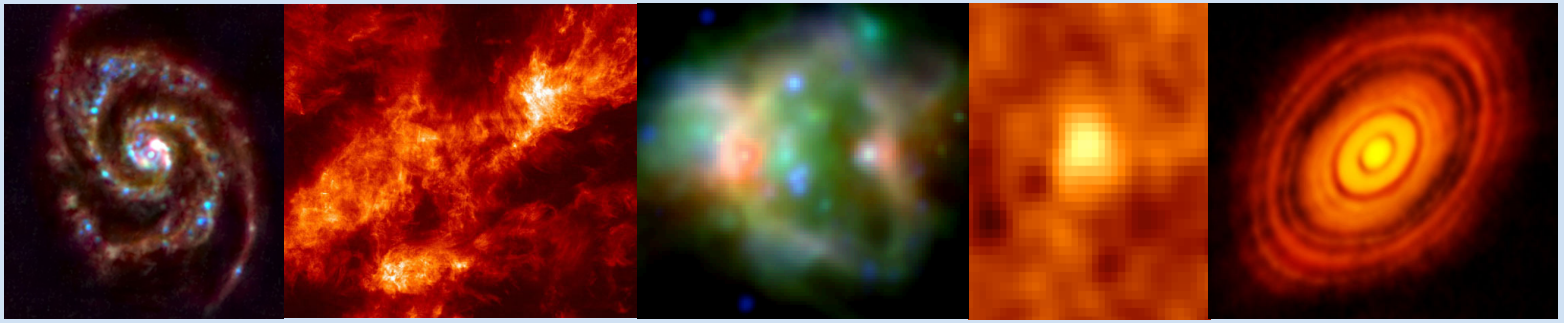
Spiral Arms from Steiman-Cameron+ 2010
(FIRAS [CII]-[NII])…very similar to Churchwell (2009)

Schede-figlie: “MWGP” (INAF-MS), “HGBS”



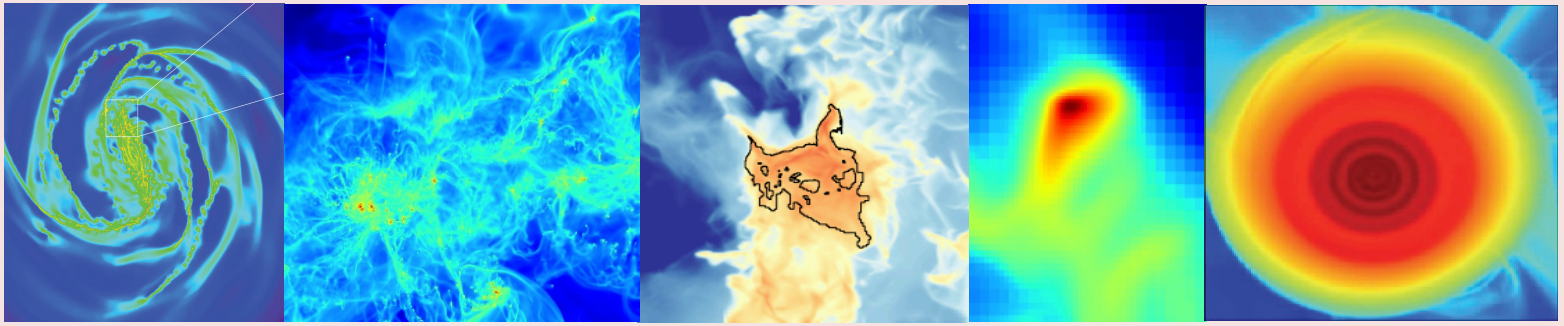
State of the art: 50 years of observations and modelling

Observations



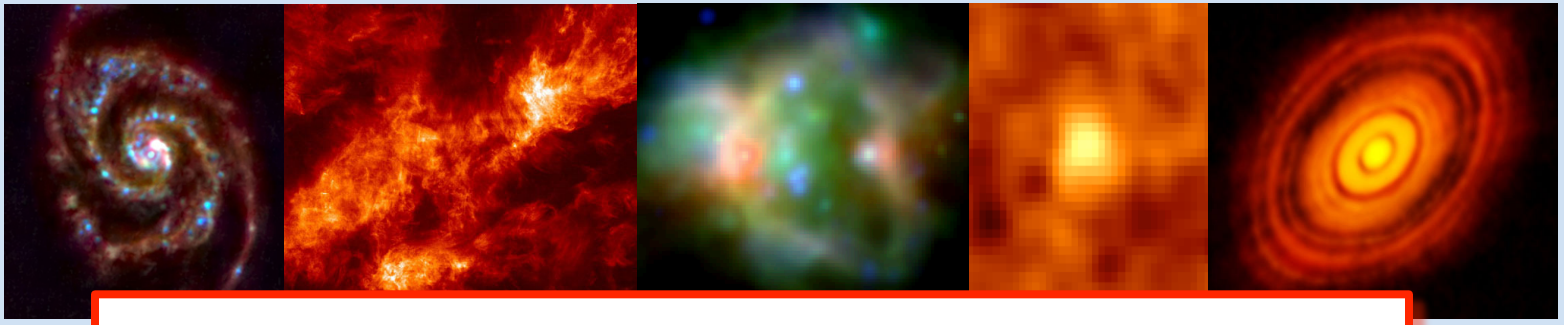
Galactic disk *Our ecosystem*	**Molecular clouds** *Largest star-forming complexes*	**Clumps** *Embedded young clusters*	**Cores** *Single/binary star forming*	**Protoplanetary disks** *Where planets form*
100,000 l.y.	100 l.y.	10 l.y.	1 l.y.	0.0001 l.y.

Theory



State of the art: 50 years of observations and modelling

Observations



DISCONNECTION

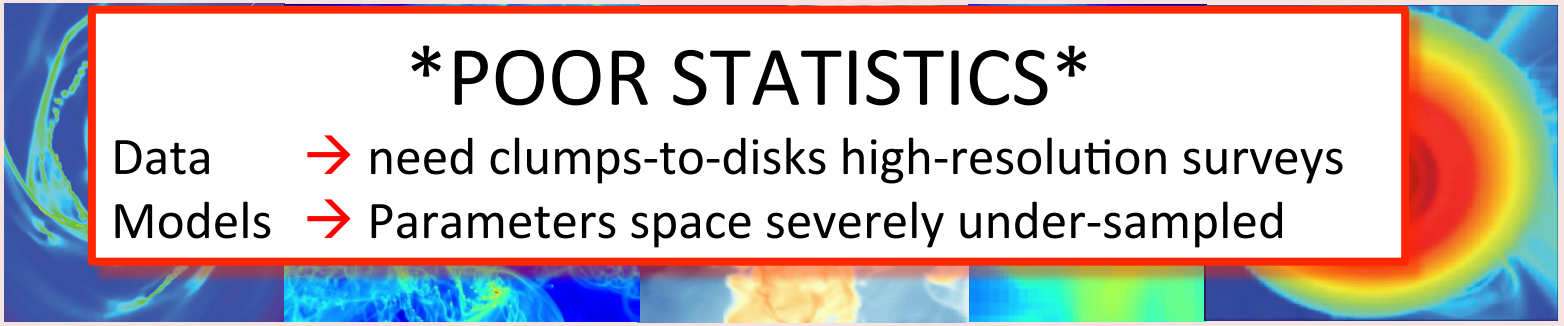
Data → "Watertight compartments" interpretations

Models → Arbitrary initial conditions

Gal ... **tary disks**

Our ecosystem	*Largest star forming complexes*	*Embedded young clusters*	*Single/binary star forming*	*Where planets form*
100,000 l.y.	100 l.y.	10 l.y.	1 l.y.	0.0001 l.y.

Theory

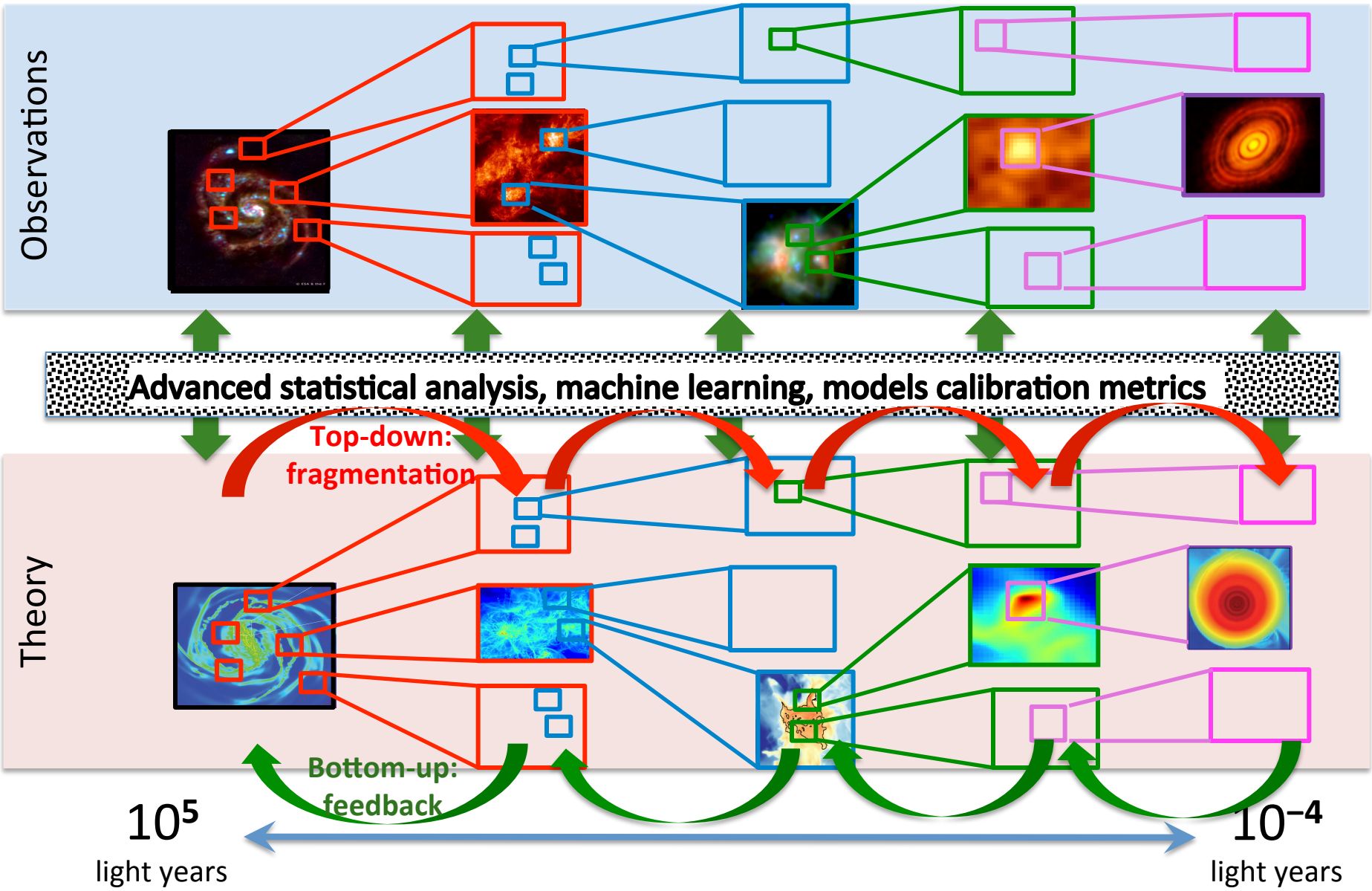


POOR STATISTICS

Data → need clumps-to-disks high-resolution surveys

Models → Parameters space severely under-sampled

Our strategy: connection and statistics

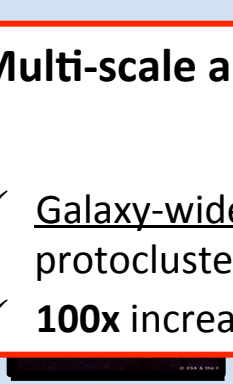


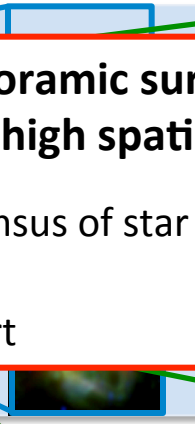
Our strategy: connection and statistics

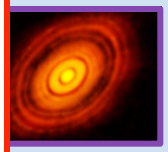
Observations

Multi-scale analysis of Galaxy-scale panoramic surveys +
New high spatial resolution surveys:

- ✓ Galaxy-wide and statistically significant census of star forming regions, young protoclusters and protoplanetary disks
- ✓ **100x** increase w.r.t. present state of the art







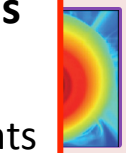
Advanced statistical analysis, machine learning, models calibration metrics

Top-down: fragmentation

Theory

Iterative series of zoom levels: Top-down → full control of initial conditions
Bottom-up → "effective modelling"

- ✓ Self-consistent and statistically significant ensemble of representative environments
- ✓ Analytical models and probability density functions to provide the general picture



Bottom-up: feedback

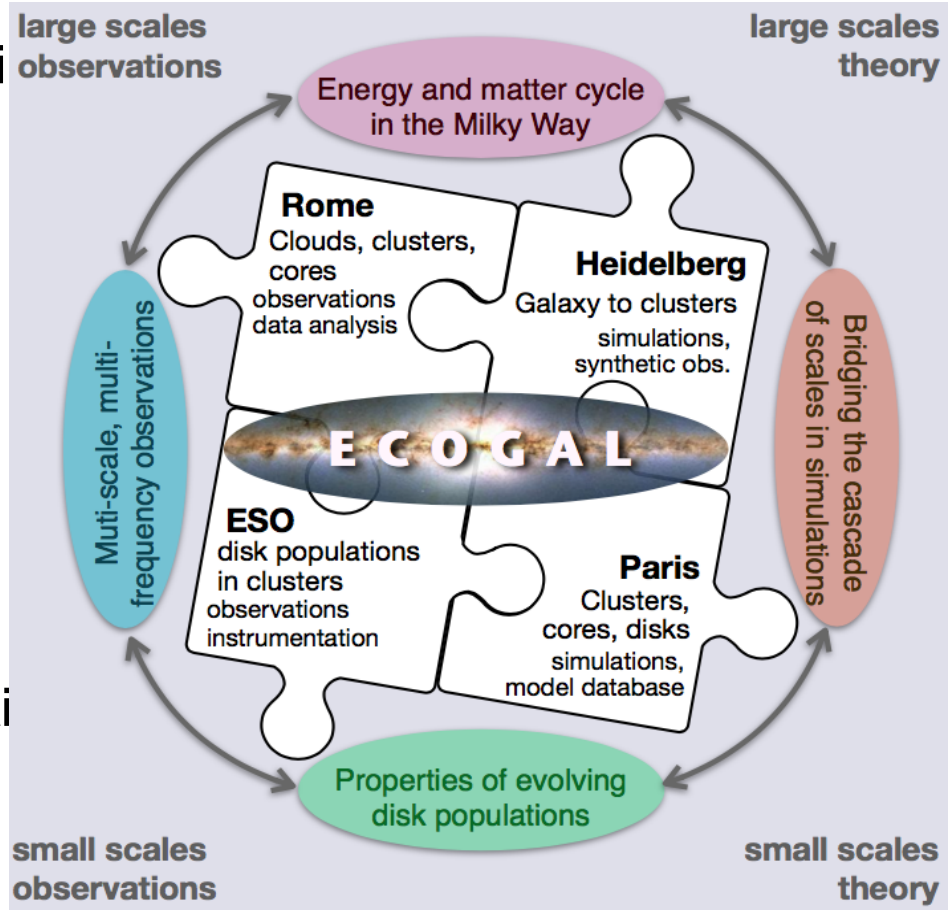
10^{5} light years

10^{-4} light years

Our team

Sergio Molinari

INAF
ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS



Ralf Klessen

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Leonardo Testi

European Southern Observatory

Patrick Hennebelle

cea

European Research Council

10M€ in total

+ 4M€ for equipment, instruments & infrastructures

Our team

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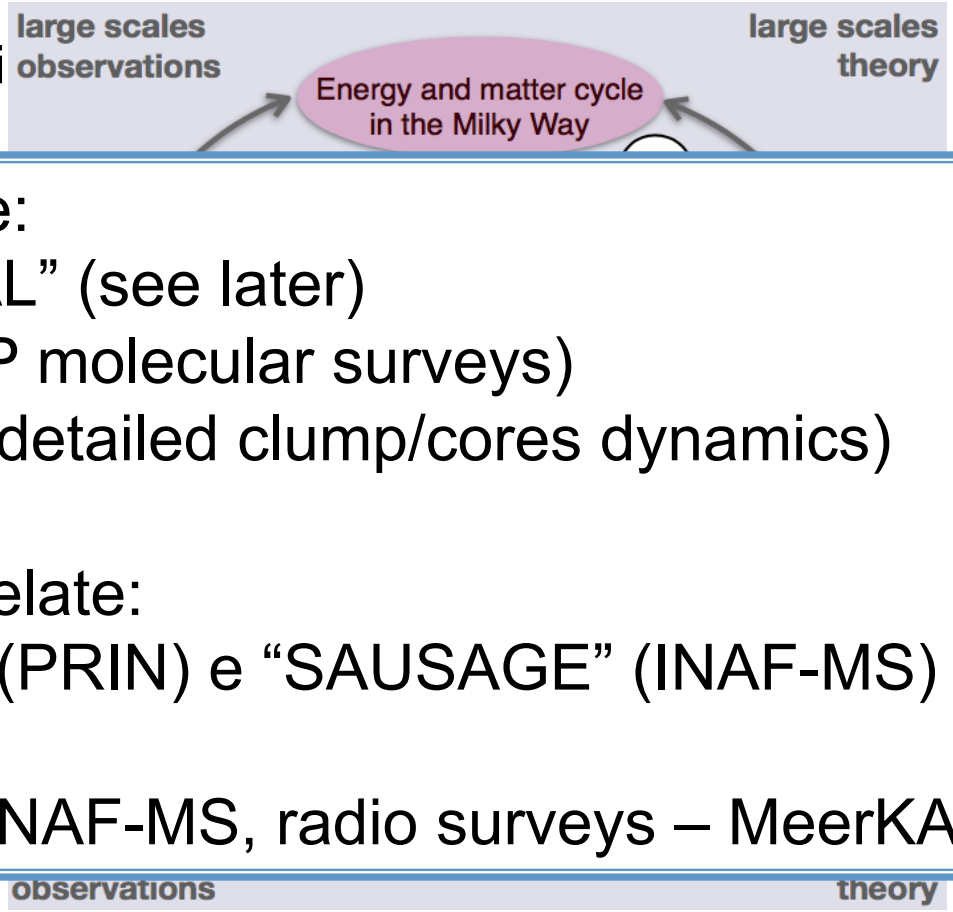
Ralf Klessen



Schede-figlie:

- "ALMAGAL" (see later)
- "FQS" (GP molecular surveys)
- "Squalo" (detailed clump/cores dynamics)

Schede correlate:

- "**ONSET**" (PRIN) e "SAUSAGE" (INAF-MS) (massive star formation)
- "RAGA" (INAF-MS, radio surveys – MeerKAT/ASKAP)

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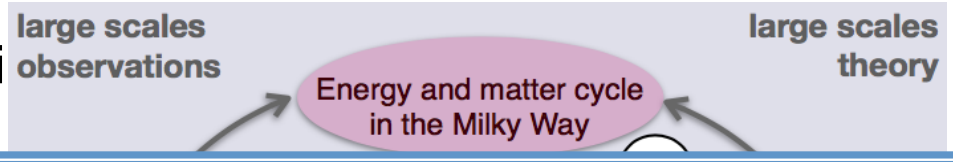

Schede-figlie:

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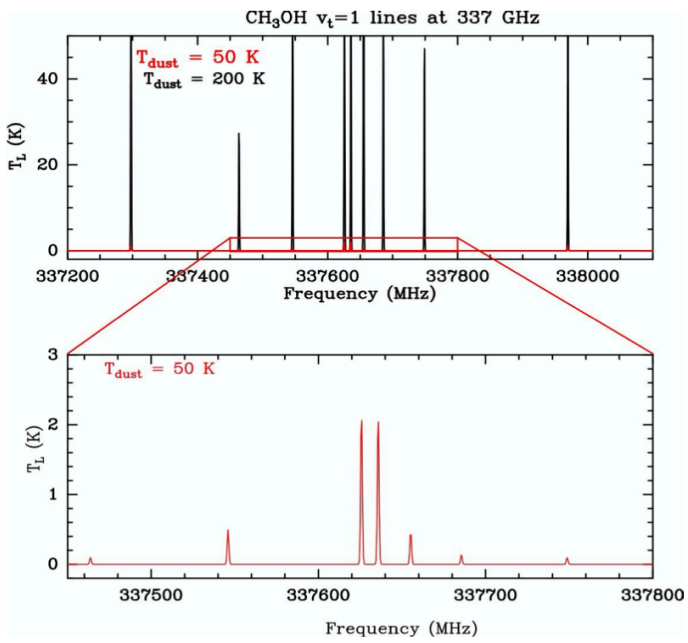
ONSET

- Track early protostellar evolution in embedded protoclusters
- Calibrate mm CH_3OH and HC_3N vibrationally excited lines (single-dish and ALMA) as proxy for internal mid-IR radiation field using
- Calibrate using synthetic protoclusters SED models
- Apply to ALMAGAL sample
- Joint AdR



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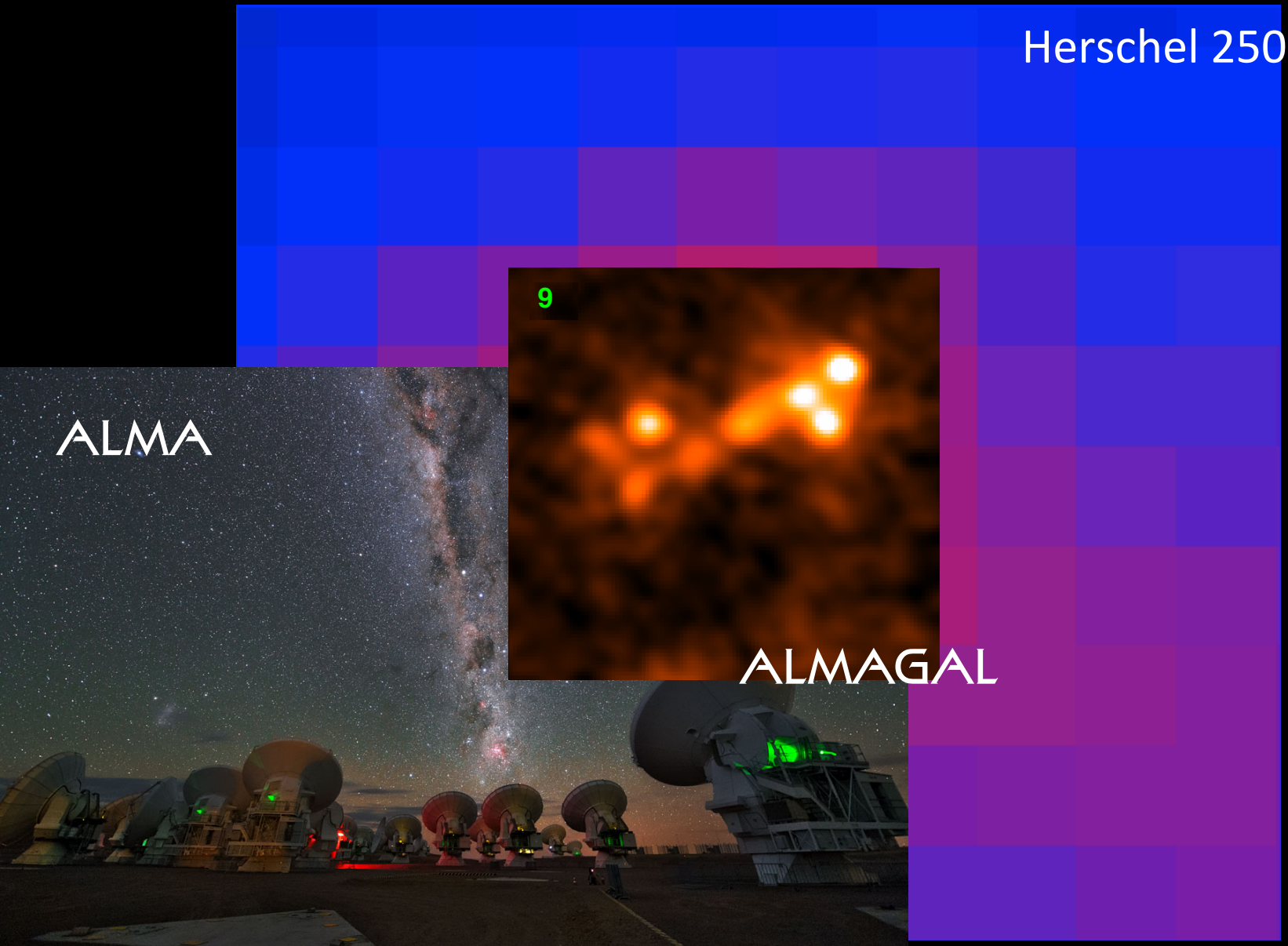
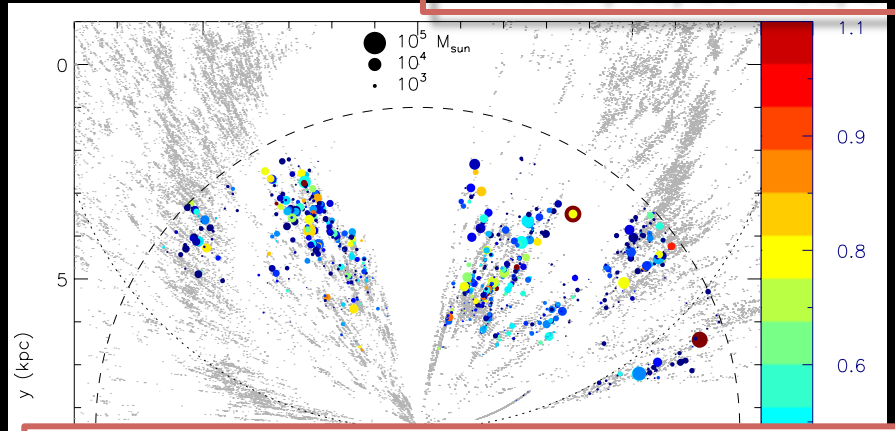
Next level of complexity: fragmentation of clumps into cores and the pathways toward ZAMS stars

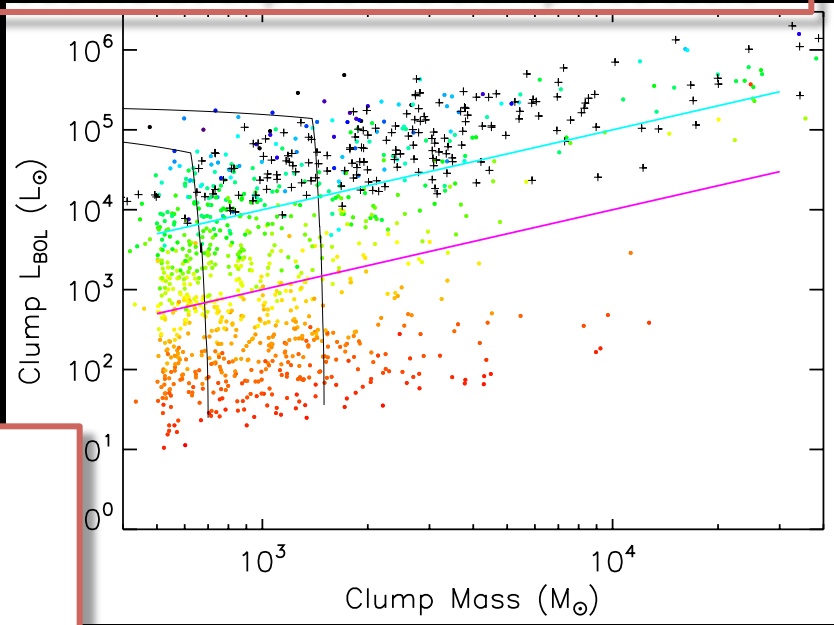


Statistics of fragmentation of clumps into cores and the pathways toward ZAMS stars

ALMAGAL: ALMA Large Project in Cycle7 to map 1000 clumps in Band 6 [λ=1mm]:

- Dust thermal continuum + CH_3CN + H_2CO + ^{13}CO + ...
- ACA/C3/C6 + C2/C5: from 1000 AU at 8kpc to the clump size scale





- Fragmentation and Mass Functions
- Clump-level Star Formation History
- Intra-clump cores dynamics
- Cores-clump feedback
- Outflows & Disks

Galaxy-wide and w.r.t. evolution

Statistics of fragmentation of clumps into cores and the pathways toward ZAMS stars

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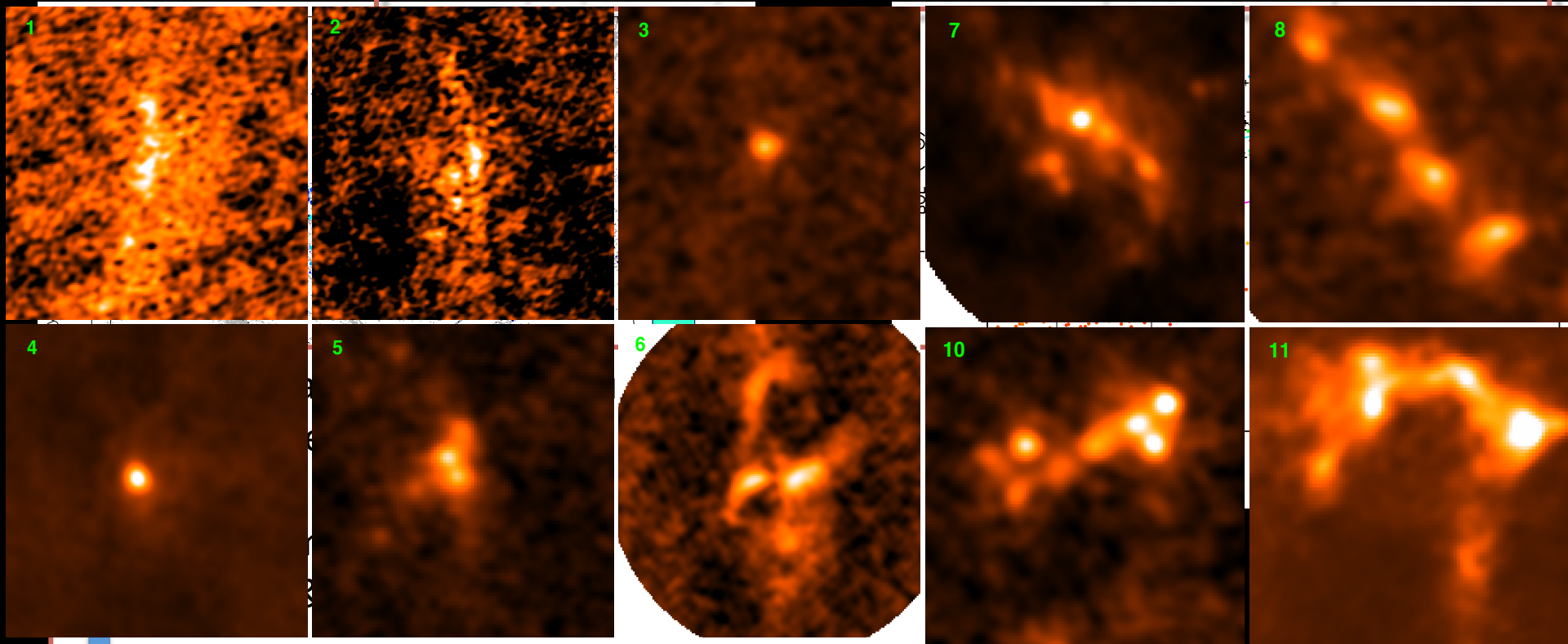
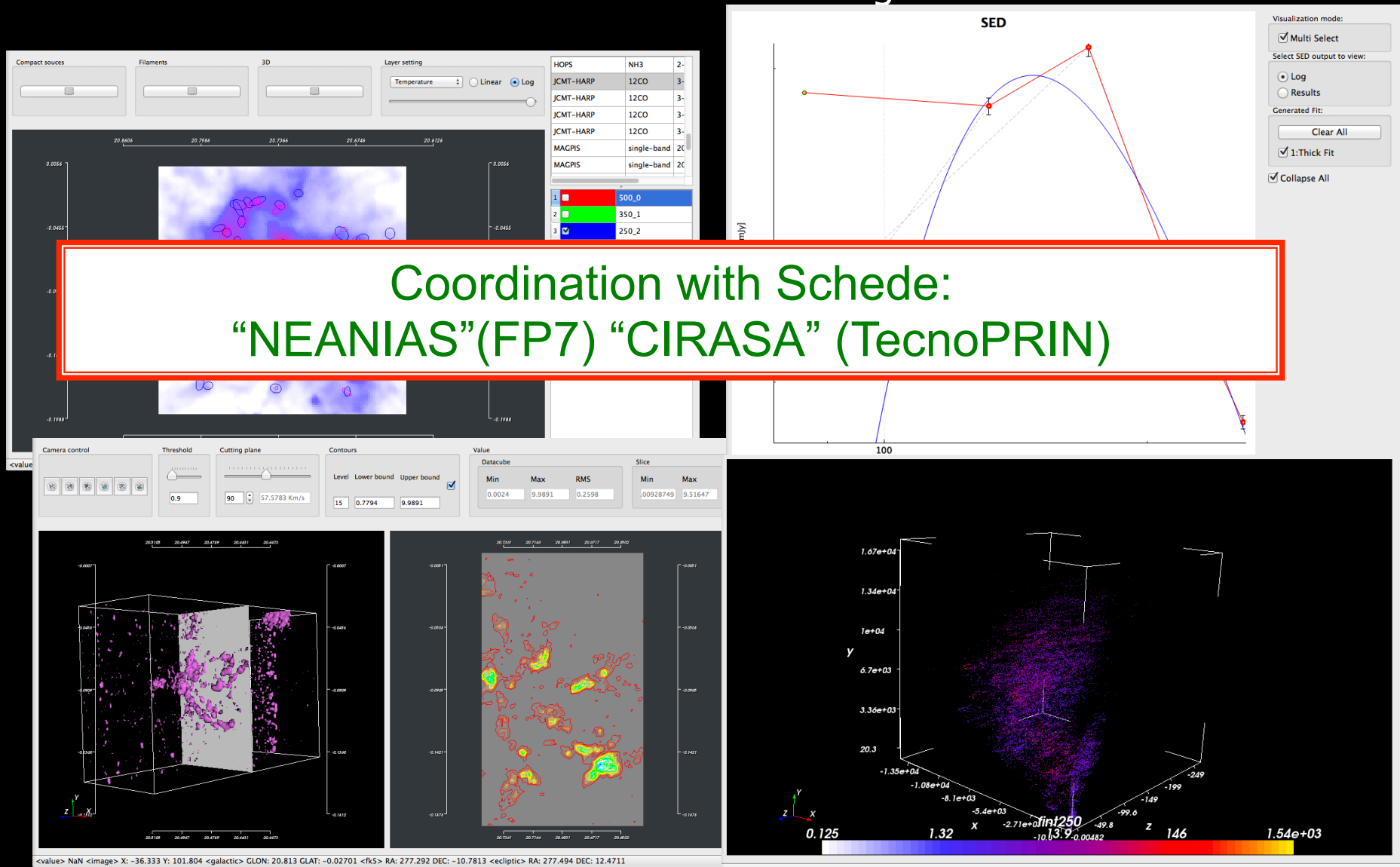


Galaxy-wide and w.r.t. evolution

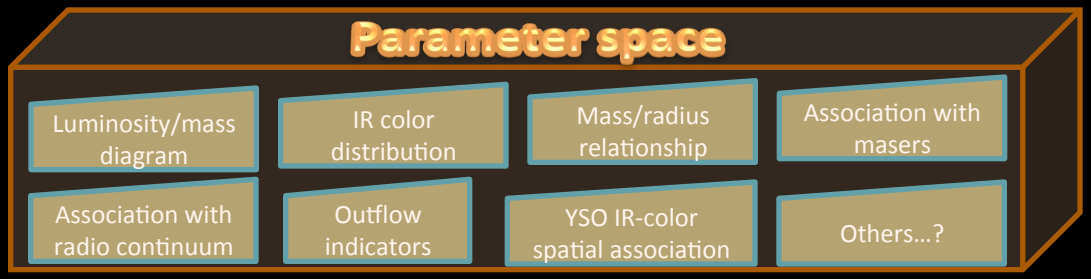
VIALACTEA Knowledge-base and Visualization

Visualization-driven access to the VIALACTEA KB: images, spectral cubes, source and filaments catalogues

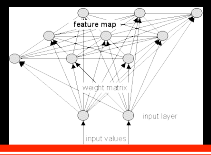


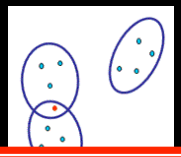
Coordination with Schede:
"NEANIAS"(FP7) "CIRASA" (TecnoPRIN)

Data-mining approach to source classification



unsupervised

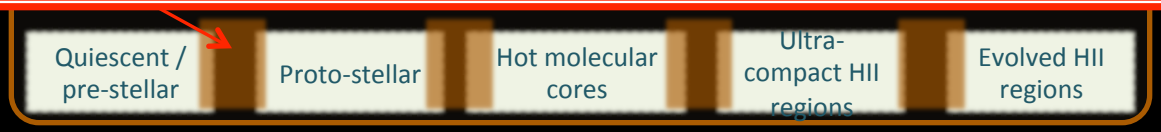


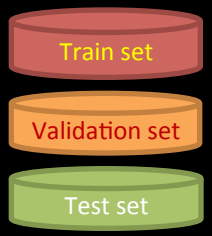


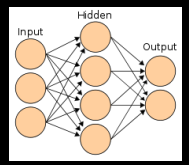
validated by science experts

Weak gated classification

Coordination with scheda: "Astroinformatics"







estimation

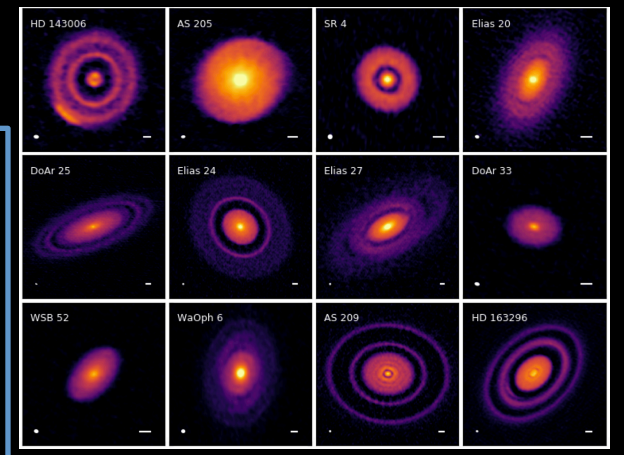
Fuzzy/cross-entropy

- Start with blind unsupervised classification
- Analyze degree and nature of clustering in the parameters space
- Map this clustering onto the tentative ground-truth sample, to confirm/modify/re-define the
- including objects that precisely map source clustering
- Run supervised classification
- Iterate.....

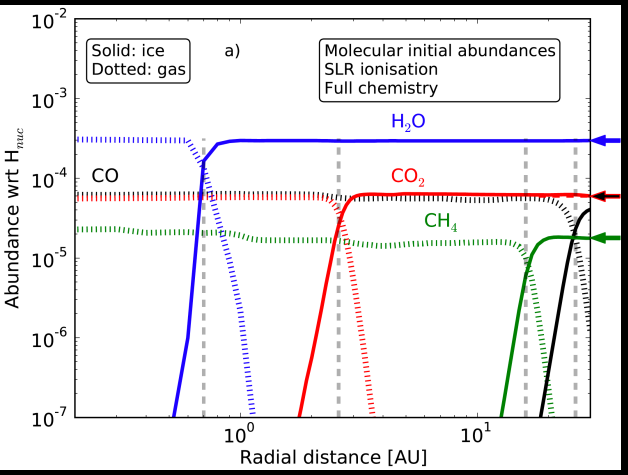
Challenge: heterogeneous information

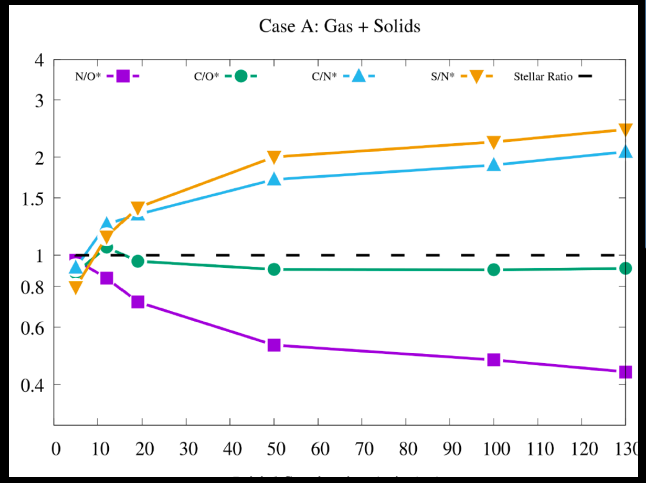
Chemical diversity in protoplanetary discs and its impact on the formation history of planets

ALMA shows widespread presence of morphological features ascribed to the presence of <u>planets at 10-100s au</u> from the star.



Disk chemical model → Resulting planet composition





Turrini et al. 2021

Migrating giant planets accrete gas & planetesimals whose chemical composition reflects that of the region of the disc out of which they formed. → **<u>Chemical tracers</u>** in planetary atmospheres can be identified and used as observables in upcoming missions →

Coordination with schede: “AMS” (INAF-MS), “ARIEL” e “HOT-ATMOS”

Criticità

- Highly productive Team: 365 refereed papers – 23000 citations – h=74 [ADS, from current IAPS group staff] + demonstrated ability to attract external funding.....no INAF soft money used to build it (ex-CNR history)

- Interstellar medium & star formation themes historically under-appreciated in INAF (and in Italy) compared to other areas, notwithstanding groups that gained exceptional international standing in the field.

- Exceedingly difficult access to critical observing facilities
  - Space-borne platforms in the infrared are cryogenically limited to few years → BIG disadvantage compared to, e.g., High-Energy. We would need extra support for science exploitation.
  - Ground-based: rely on ALMA and the good grace of IRAM-PdB. We could have joined JCMT....we could join IRAM....

- Cultural problem in INAF: the 5μm-5mm spectral range is in the optical or in the radio ?