"ESO in the 2020s", 20th January 2015

High mass star and cluster formation

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Talk outline

- Long term goal
- Fundamental barriers to progress
- Recent progress in the field: theory
- Major open questions
- Recent progress in the field: observations
- Looking forward to 2020s (and beyond)

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Goal = illustrative, not exhaustive

Background to frame scene moving forward.

See Tan+14 PPVI review for more details

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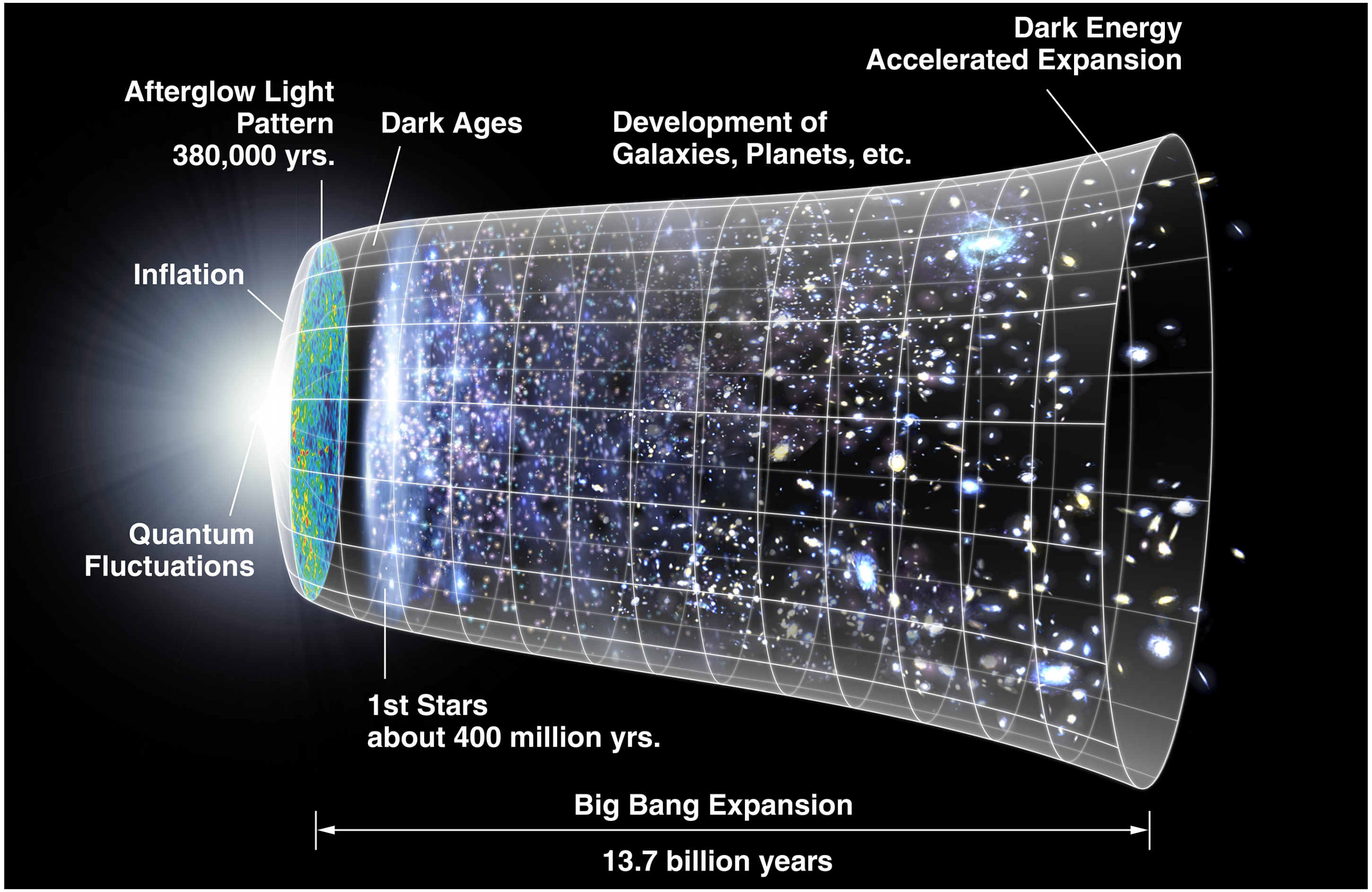
Conversion of gas to stars and planets: pillar of astrophysics and cosmology

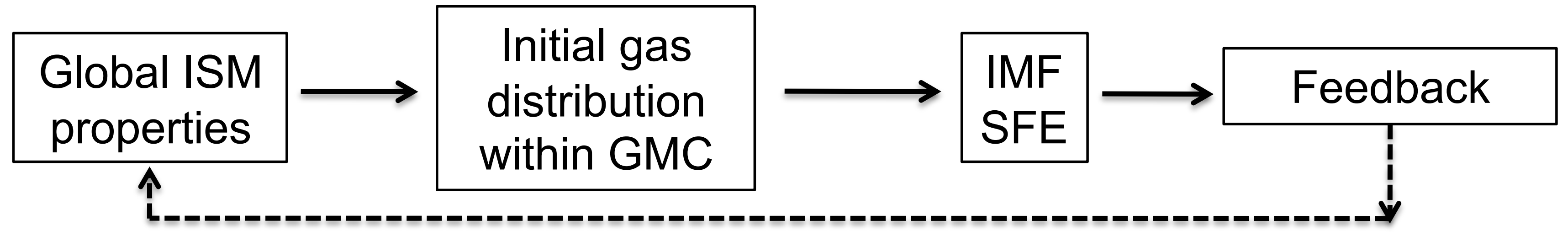


High mass stars dominate the energy cycles and chemical enrichment of galaxies across cosmic time

Pivotal role in the mass assembly of the Universe.

Long-term goal

End-to-end description of star formation and feedback as a function of environment across cosmic time



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- Recent progress in the field: theory
- Major open questions
- Recent progress in the field: observations
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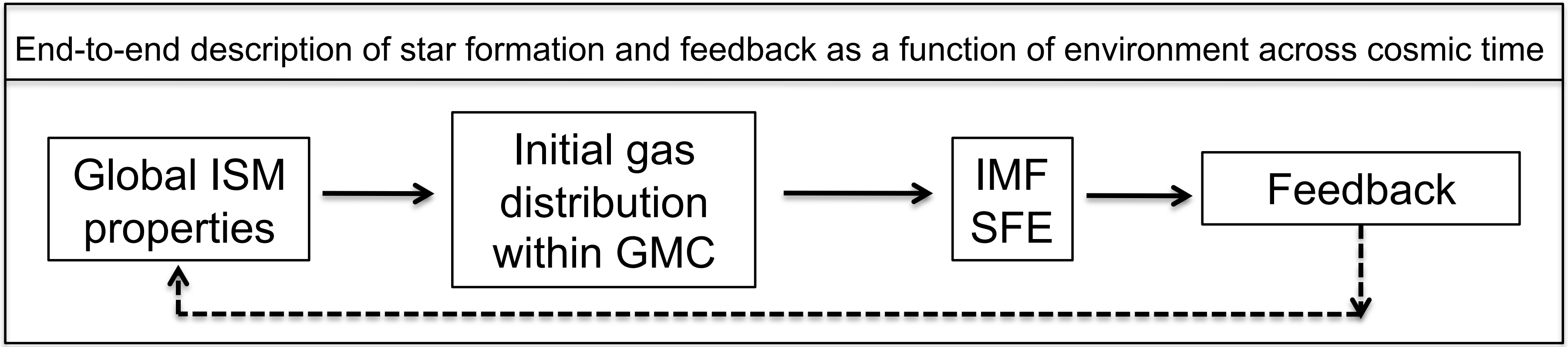
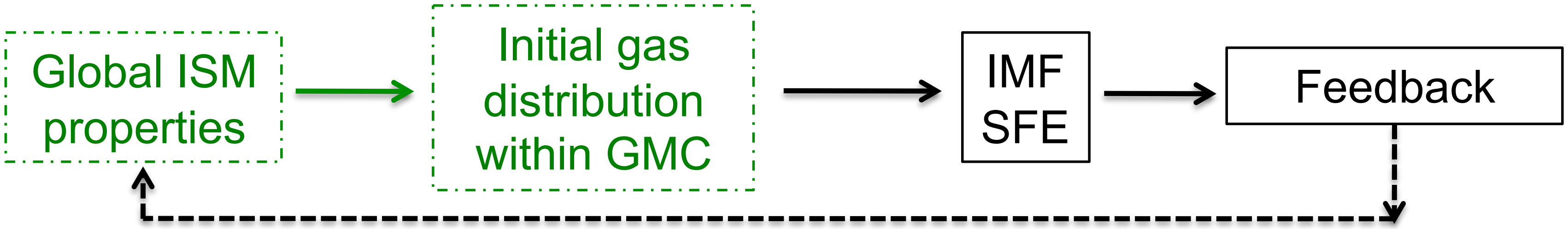
Recent progress in the field: theory



Recent progress in the field: theory

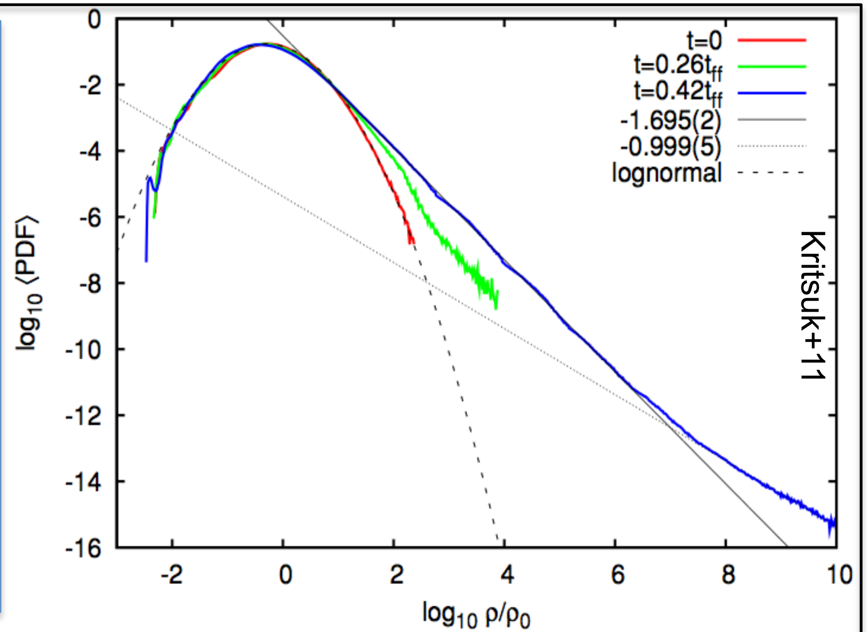
End-to-end description of star formation and feedback as a function of environment across cosmic time



Turbulence sets initial gas density distribution

β, α, M_S, M_A

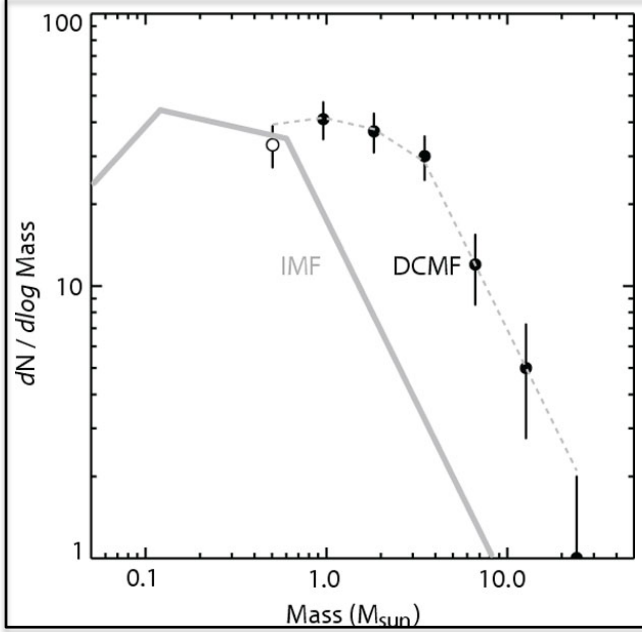
- β — *Degree of compression*
- α — *Gravitational stability*
- M_S — *Shock strength*
- M_A — *Mag. field strength*



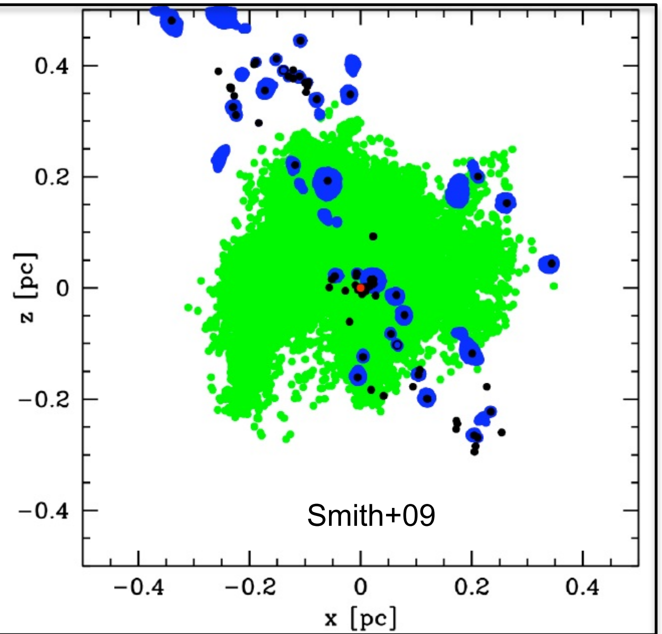
Hennebelle & Chabrier, Padoan & Nordlund, Krumholz & McKee, Hopkins, Klessen, Federath → Padoan+14 PPVI review

Recent progress in the field: theory

End-to-end description of star formation and feedback as a function of environment across cosmic time



Two extreme scenarios

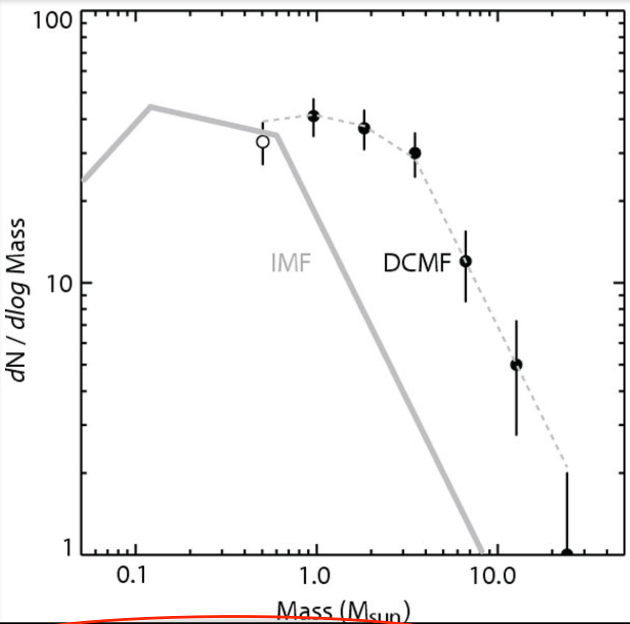


Bonnell+01, McKee & Tan 03, Smith+09, Bate+, many others …

? Recent progress in the field: theory

End-to-end description of star formation and feedback as a function of environment across cosmic time

Global ISM properties → Initial gas distribution within GMC → IMF SFE → Feedback ⇢ Global ISM properties



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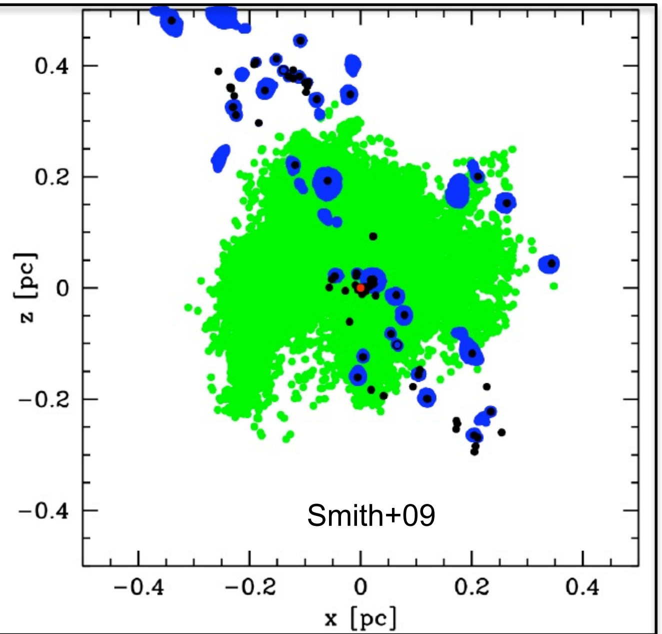

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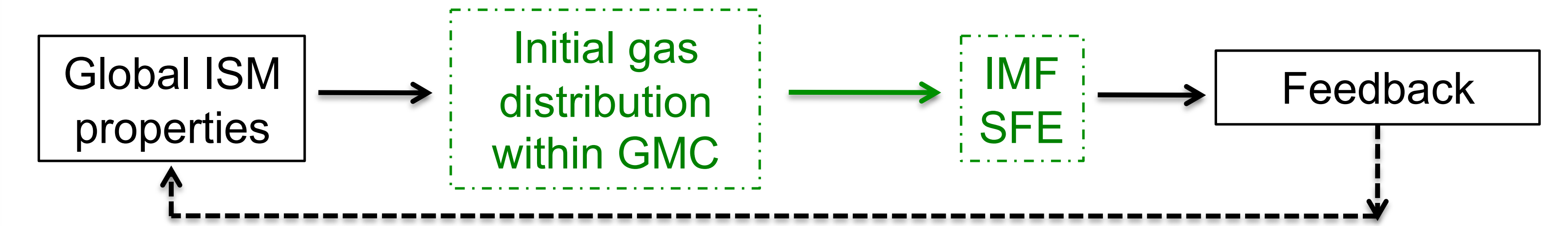

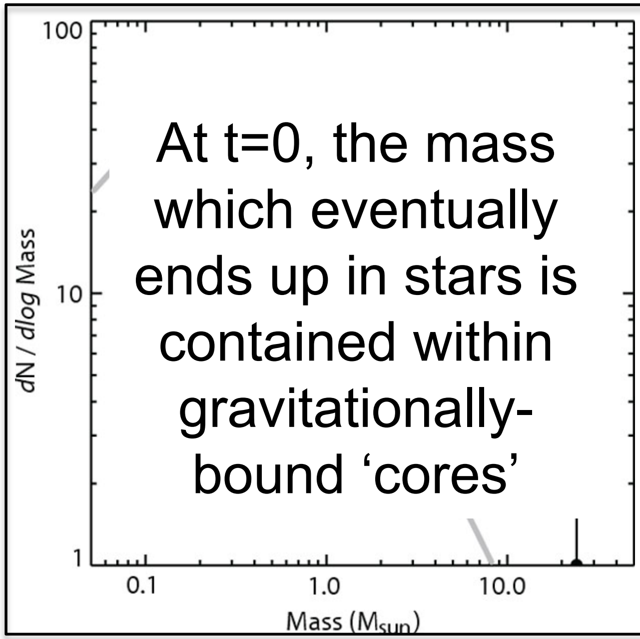

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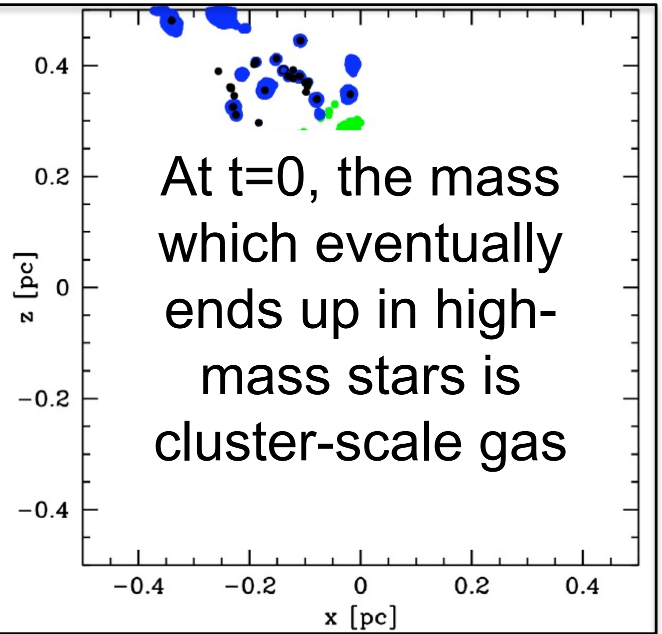
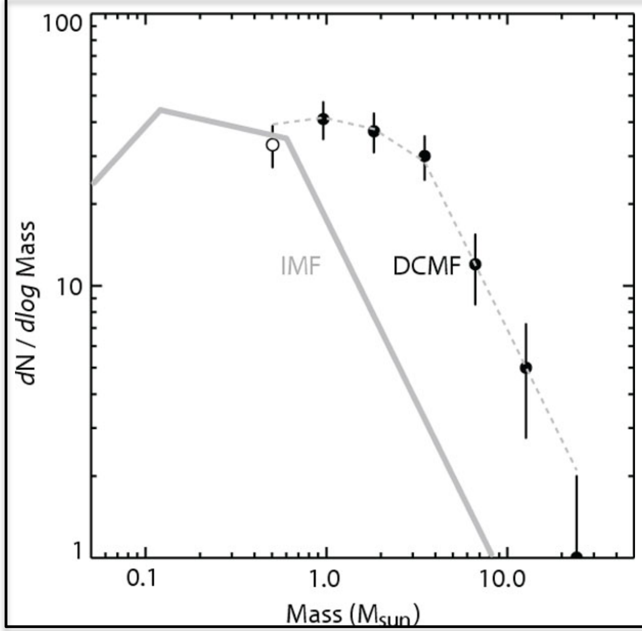


Bonnell+01, McKee & Tan 03, Smith+09, Bate+, many others …

Recent progress in the field: simulations

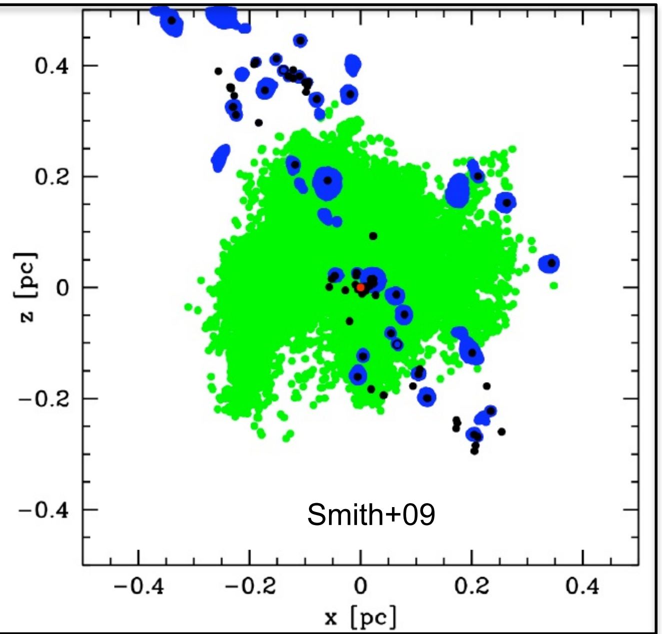
End-to-end description of star formation and feedback as a function of environment across cosmic time

(Krumholz+ 07, 12, Hennebelle+ 11, Commercon+ 11, Myers+ 13)



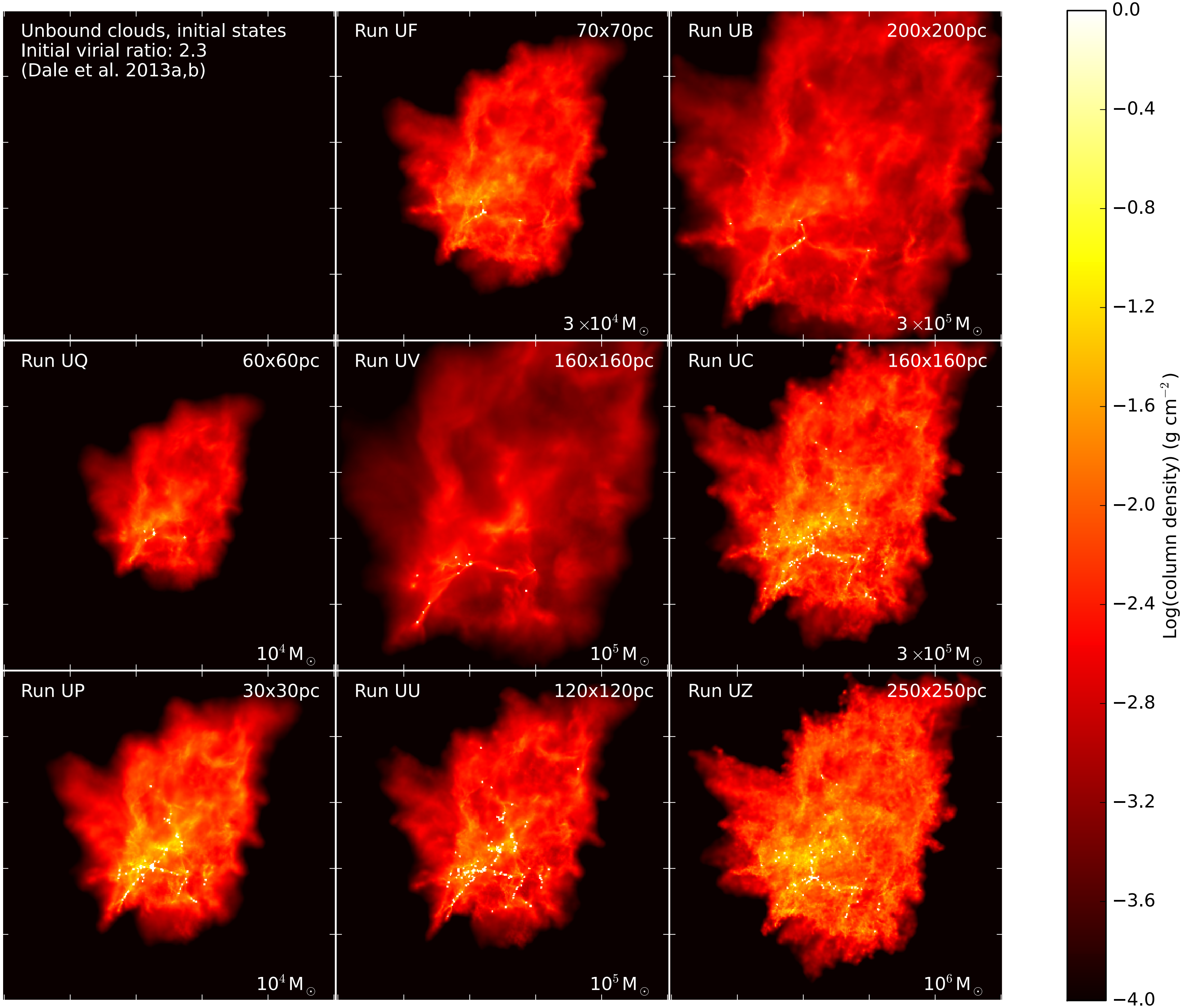
Feedback ↑
+
Initial density fluctuations ↑
+
Turbulence driving ↑
=
Fraction of M_* from initial "core" ↑

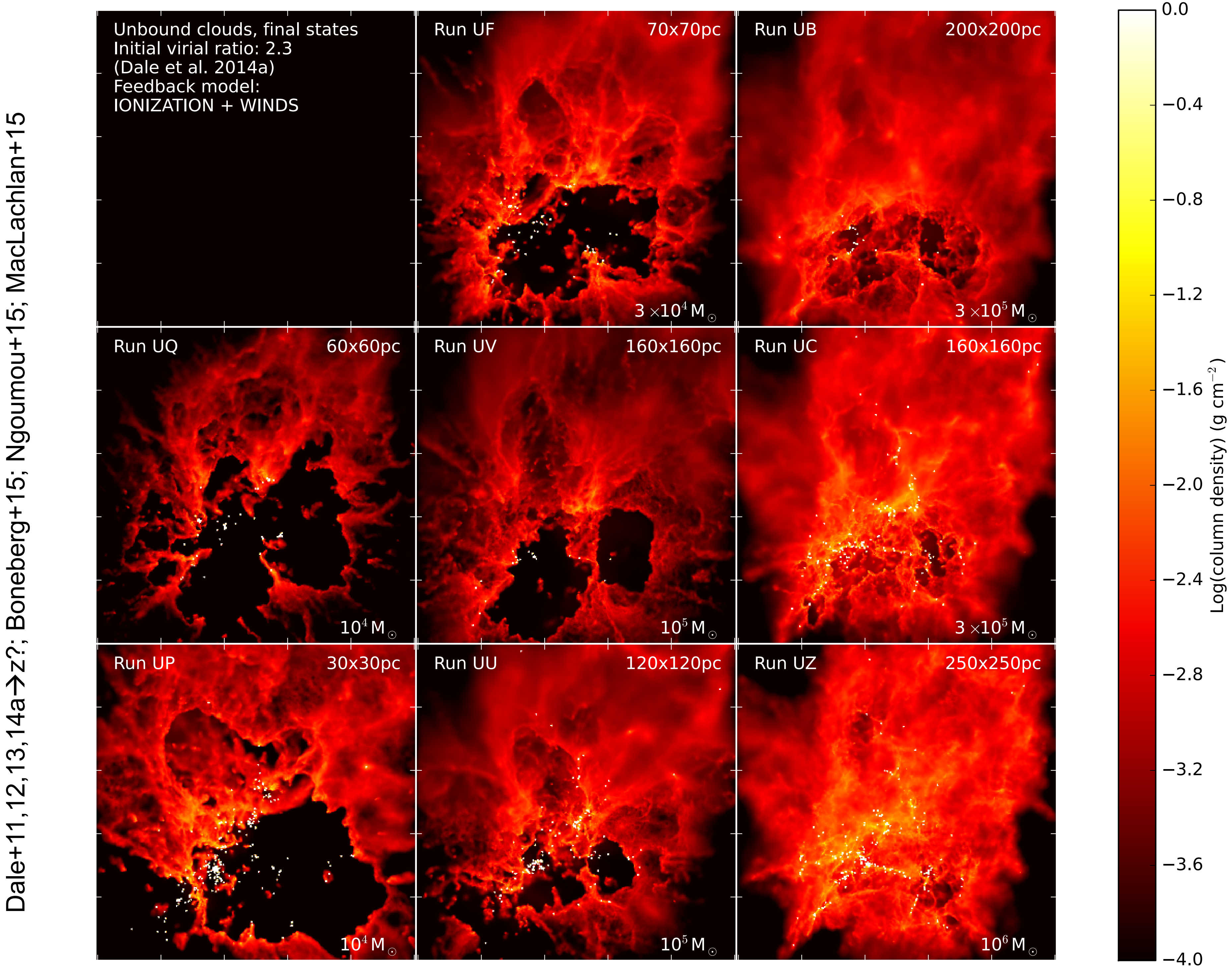
Bonnell+04, Peters+10a,b, Wang+10, Girichidis+12, Krumholz+12,



Dale+ 05, Bisbas+ 09, Fryxell+00, Li+12, Krumholz+07, Commercon+11, Peters+10, Wang+10, Cunningham+11, Kuiper+10, Clark/Glover

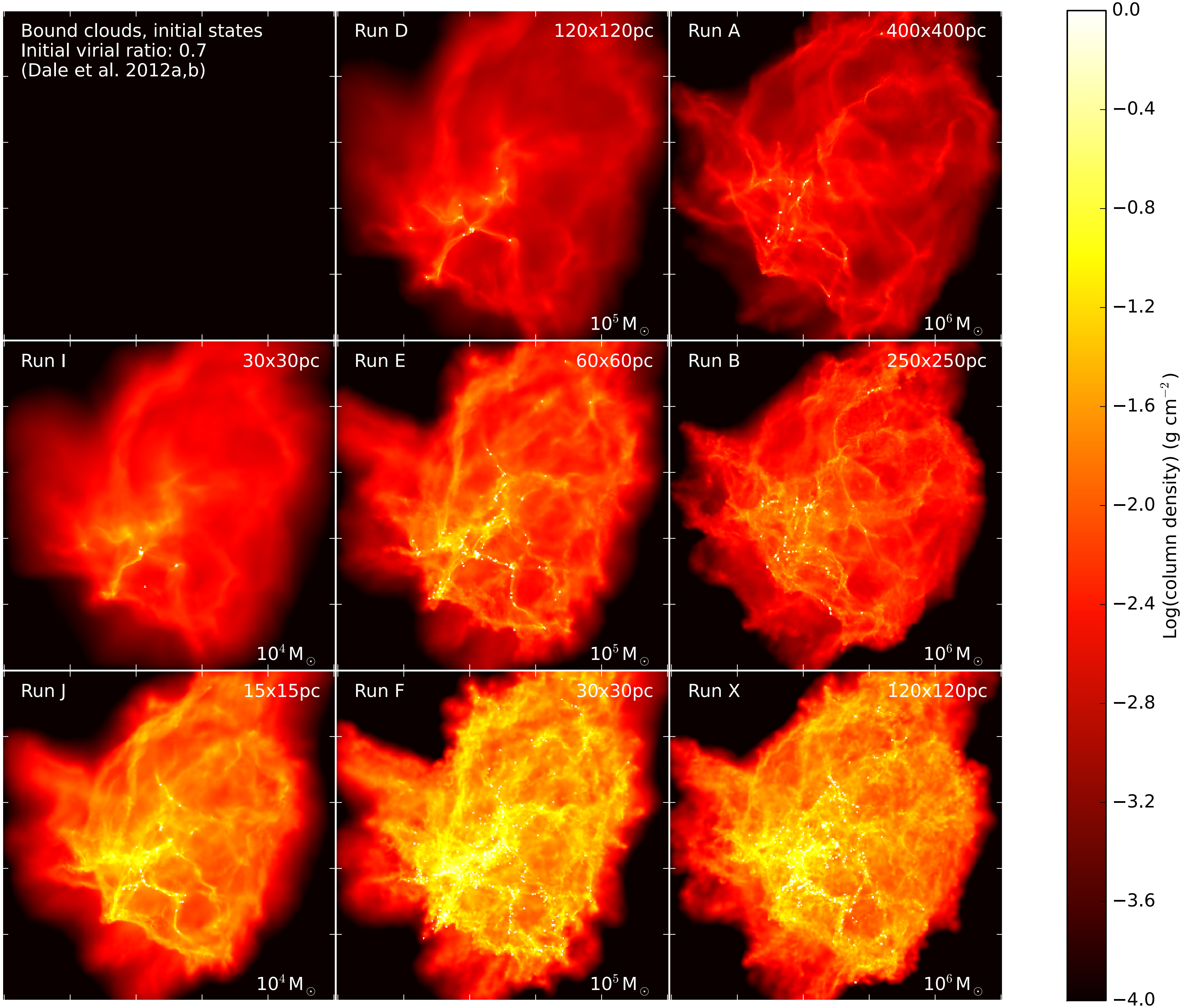
Dale+11,12,13,14a→z?; Boneberg+15; Ngoumou+15; MacLachlan+15

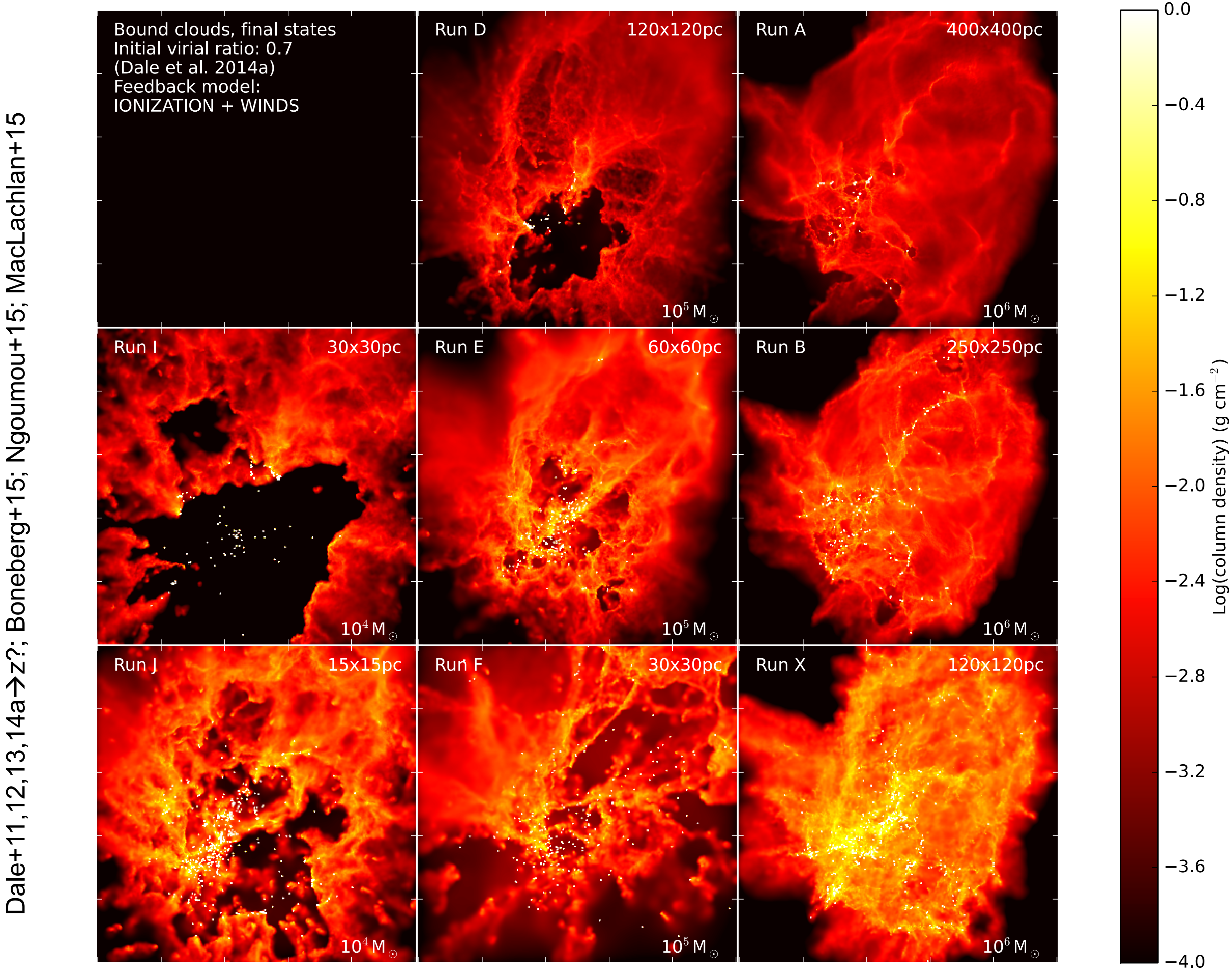




Dale+11,12,13,14a→z?; Boneberg+15; Ngoumou+15; MacLachlan+15
Unbound clouds, final states
Initial virial ratio: 2.3
(Dale et al. 2014a)
Feedback model:
IONIZATION + WINDS
Run UF
70x70pc
3 ×10⁴ M☉
Run UB
200x200pc
3 ×10⁵ M☉
Run UQ
60x60pc
10⁴ M☉
Run UV
160x160pc
10⁵ M☉
Run UC
160x160pc
3 ×10⁵ M☉
Run UP
30x30pc
10⁴ M☉
Run UU
120x120pc
10⁵ M☉
Run UZ
250x250pc
10⁶ M☉
Log(column density) (g cm⁻²)
0.0
−0.4
−0.8
−1.2
−1.6
−2.0
−2.4
−2.8
−3.2
−3.6
−4.0

Dale+11,12,13,14a→z?; Boneberg+15; Ngoumou+15; MacLachlan+15

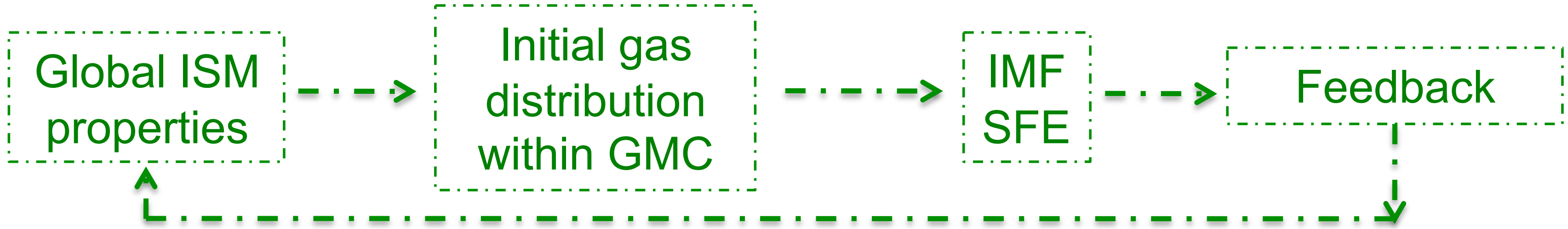


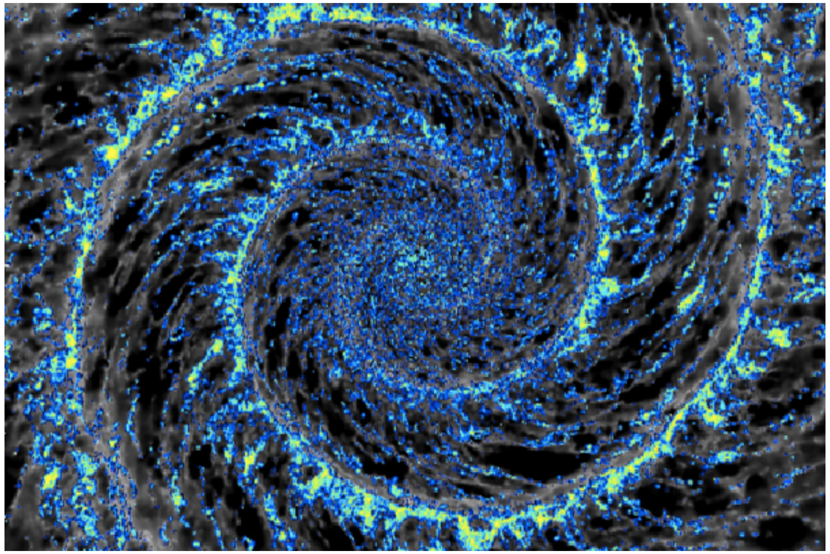


Dale+11,12,13,14a→z?; Boneberg+15; Ngoumou+15; MacLachlan+15
Bound clouds, final states
Initial virial ratio: 0.7
(Dale et al. 2014a)
Feedback model:
IONIZATION + WINDS
Run D
120x120pc
10^5 M$_\odot$
Run A
400x400pc
10^6 M$_\odot$
Run I
30x30pc
10^4 M$_\odot$
Run E
60x60pc
10^5 M$_\odot$
Run B
250x250pc
10^6 M$_\odot$
Run J
15x15pc
10^4 M$_\odot$
Run F
30x30pc
10^5 M$_\odot$
Run X
120x120pc
10^6 M$_\odot$
0.0
−0.4
−0.8
−1.2
−1.6
−2.0
−2.4
−2.8
−3.2
−3.6
−4.0
Log(column density) (g cm^{-2})

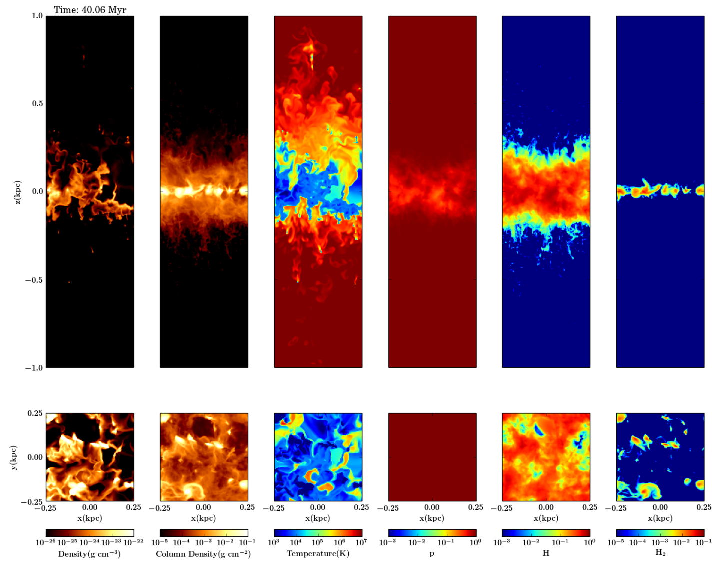
Recent progress in the field: simulations

End-to-end description of star formation and feedback as a function of environment across cosmic time





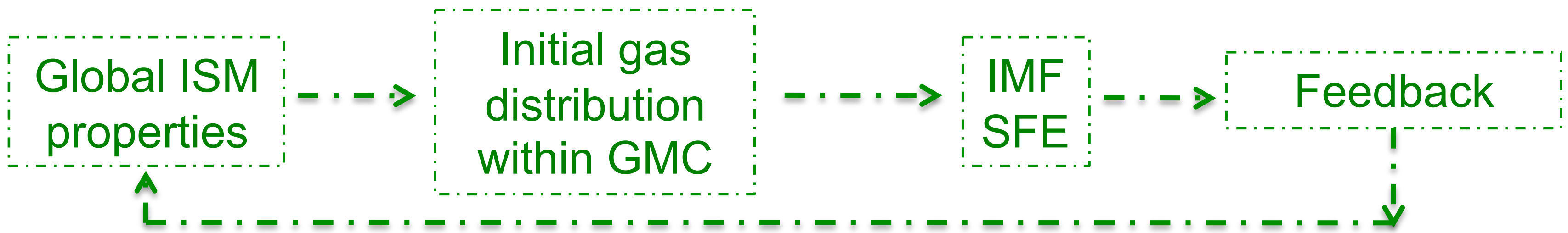
Dobbs+, Bonnell+, Renaud, Emsellem+



SILCC: Walch, Peters, Klessen, Clark, Naab, …

Recent progress in the field: simulations

End-to-end description of star formation and feedback as a function of environment across cosmic time



<u>“Sims 2020” and beyond</u>

Simulations with fully self-consistent initial conditions and full range of feedback

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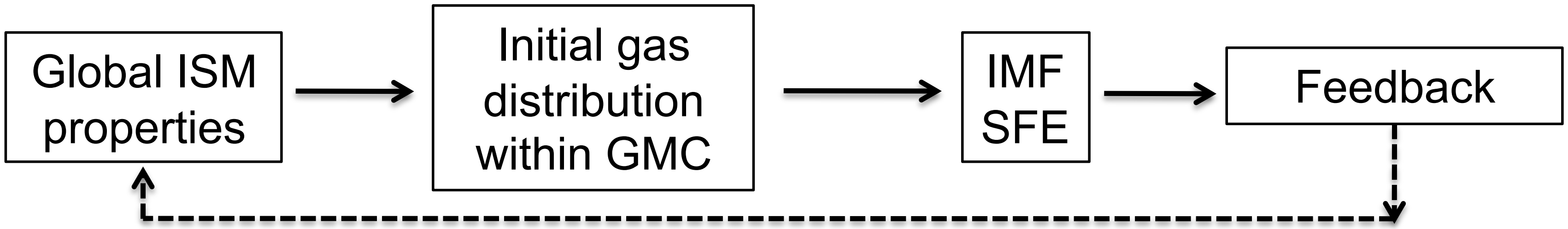
Some major open questions

End-to-end description of star formation and feedback as a function of environment across cosmic time



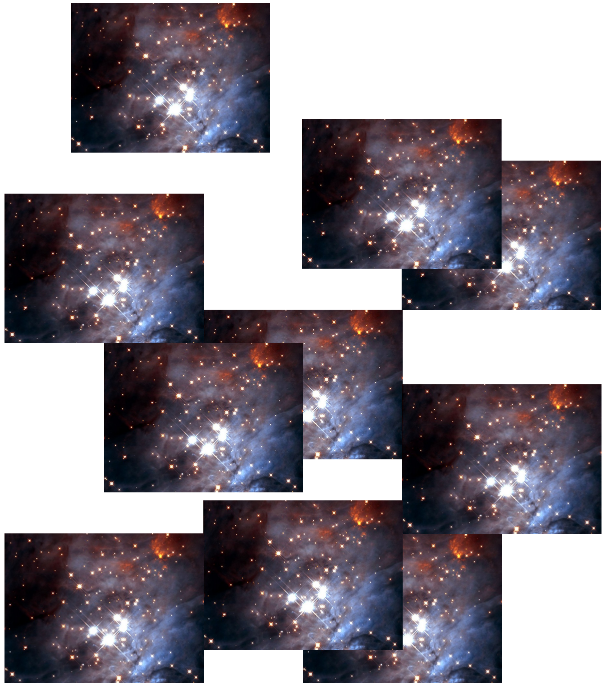
1. Where does the mass that ultimately end up on a high mass star come from?

2. What are the dominant physical mechanisms controlling this process and do they vary with environment?

3. How are the resulting stellar populations affected by global ISM properties?

Stochastic vs sorted sampling of IMF

10 x Orion Nebula Cluster



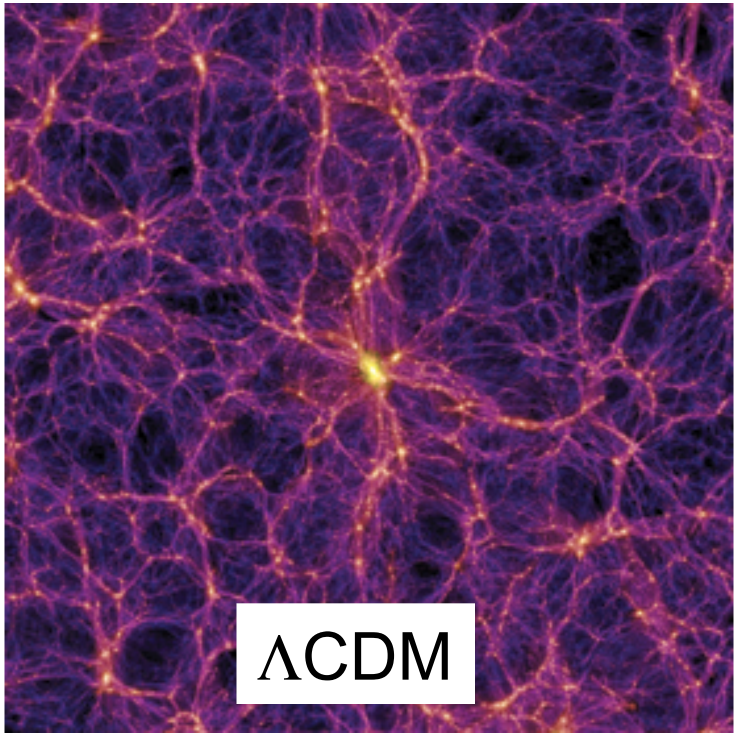
$M_* \sim 10 \times 5000\ M_{sun}$

? = ?

1 x R136

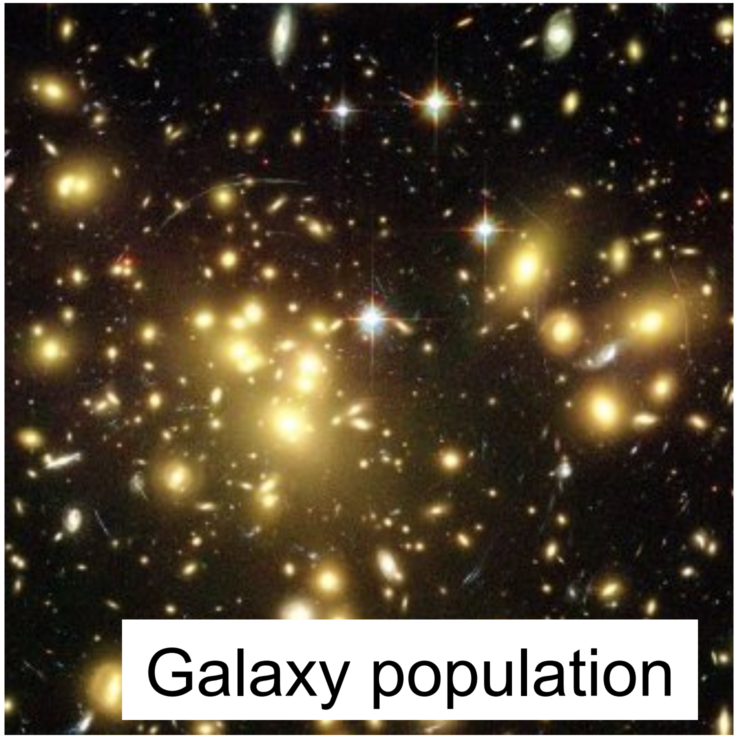
$M_* \sim 1 \times 50{,}000\ M_{sun}$

Fundamental disconnect between SF recipes and theory/observations

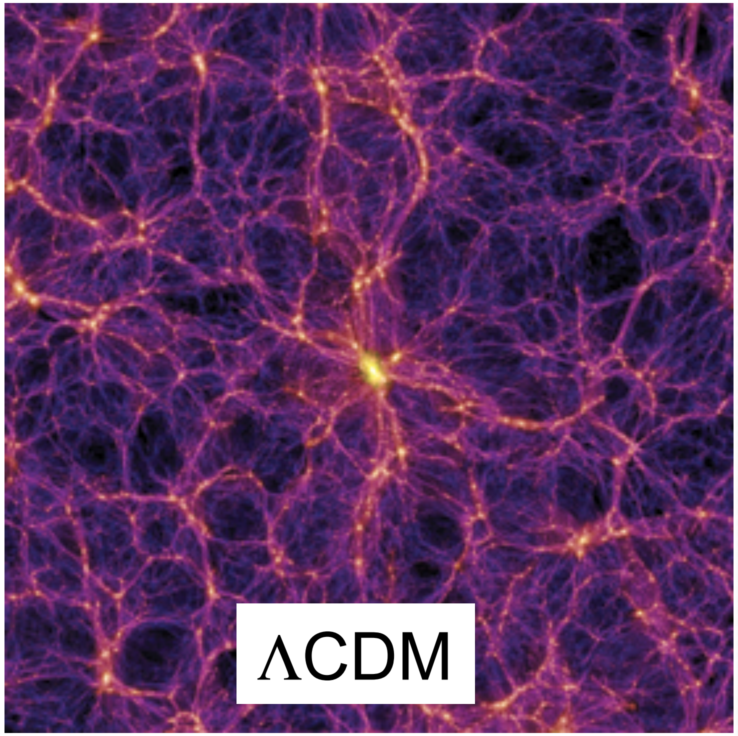


SF recipes

↔



Fundamental disconnect between SF recipes and theory/observations

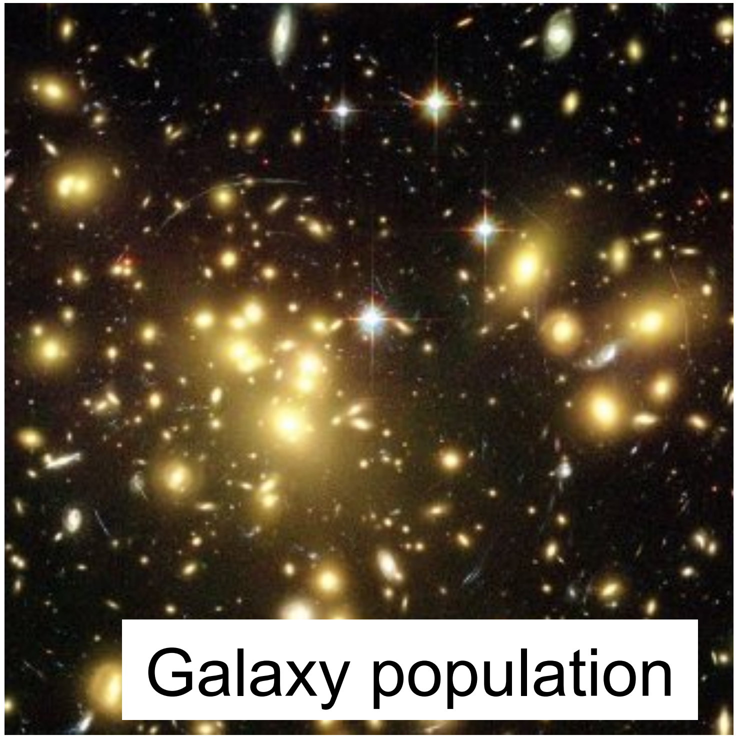


SF recipes

Fixed
t_{SF}, ε_{SF}

↔

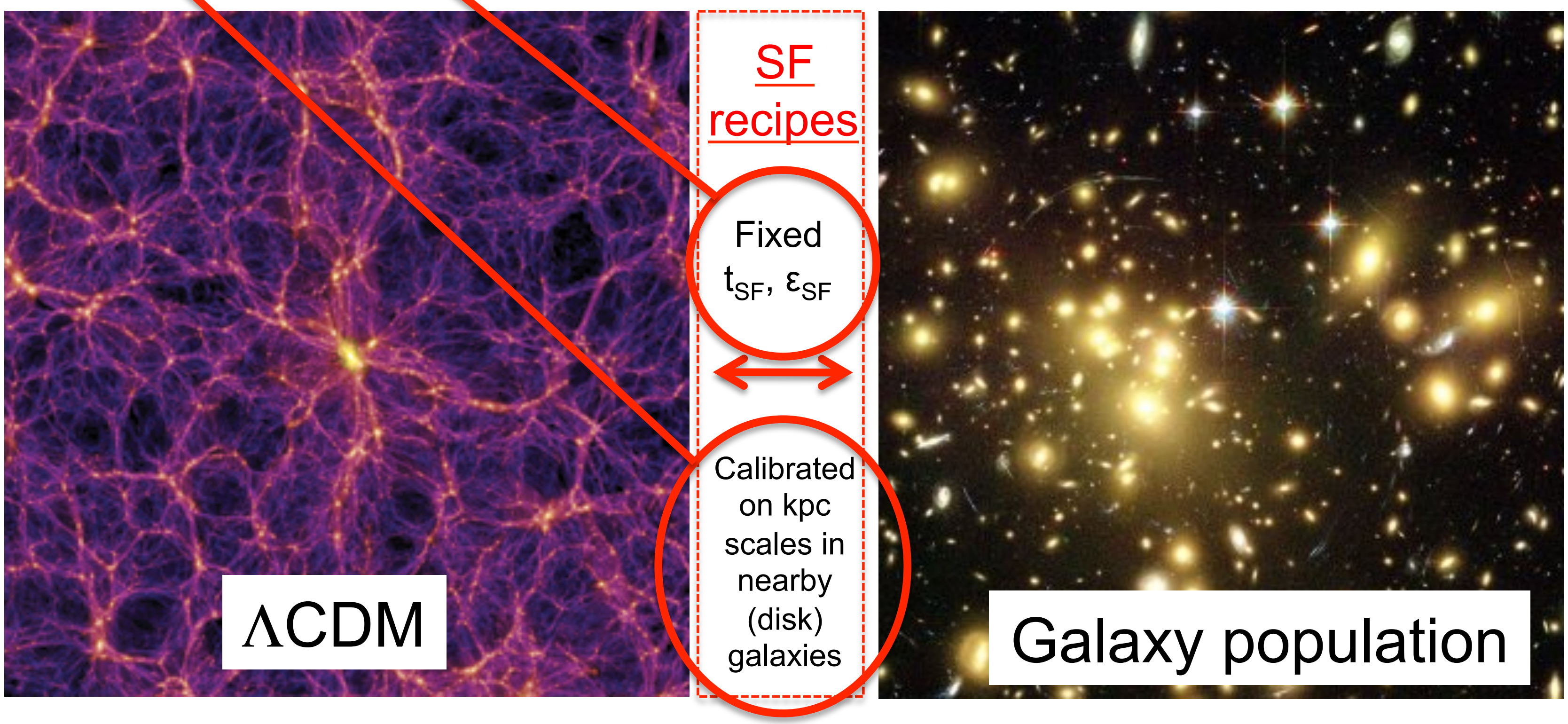
Calibrated on kpc scales in nearby (disk) galaxies



Fundamental disconnect between SF recipes and theory/observations

Observed order of magnitude deviations from calibrated values as a function of environment

Observed to break down on sub-kpc (cloud) scales



Fundamental disconnect between SF recipes and theory/observations

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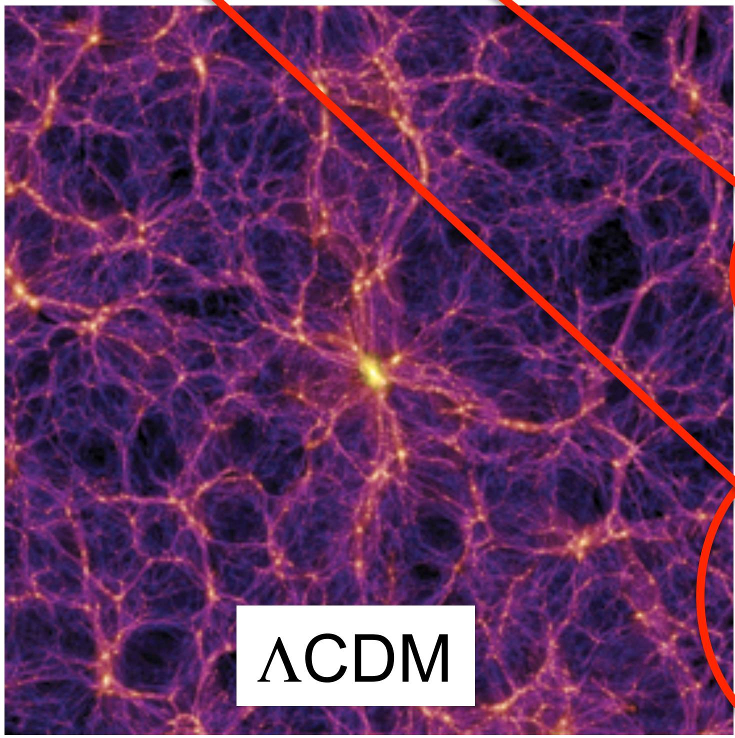

SF recipes

Fixed t_{SF}, ε_{SF}

Calibrated on kpc scales in nearby (disk) galaxies

Theory predicts order of magnitude dependence of SFR_{ff} on global initial conditions (β, α, M_S, M_A)

Some major open questions

Answering these questions: observational perspective

Building self-consistent, end-to-end understanding requires:

Following process of stellar mass assembly and feedback as a function of:
(i) all known SF environments
(ii) ***absolute*** time

1. Where does the mass that ultimately end up on a high mass star come from?
2. What are the dominant physical mechanisms controlling this process and do they vary with environment?
3. How are the resulting stellar populations affected by global ISM properties?

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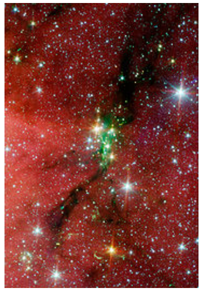
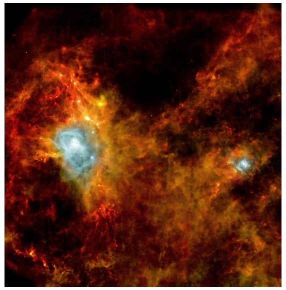
Observational issues

1. “Snapshot-itis”

Observations only ever get a single snapshot of a process lasting ~Myr

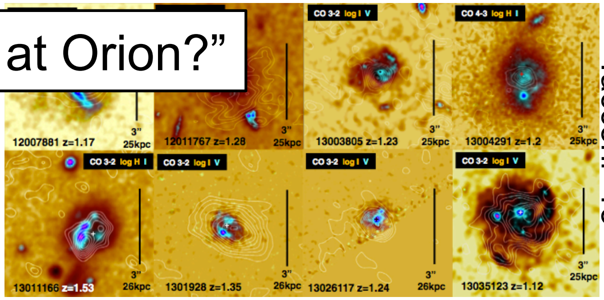




2. “My telescope is not big enough!”

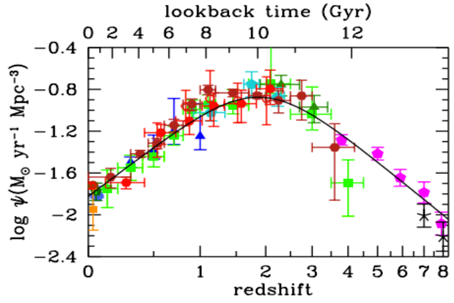
For the foreseeable future, observations will only be able resolve individual forming high-mass stars within MW, LMC, SMC


3. “Why can’t we just look at Orion?”

Can obs of MW, LMC, SMC probe full range of SF environments in Universe?

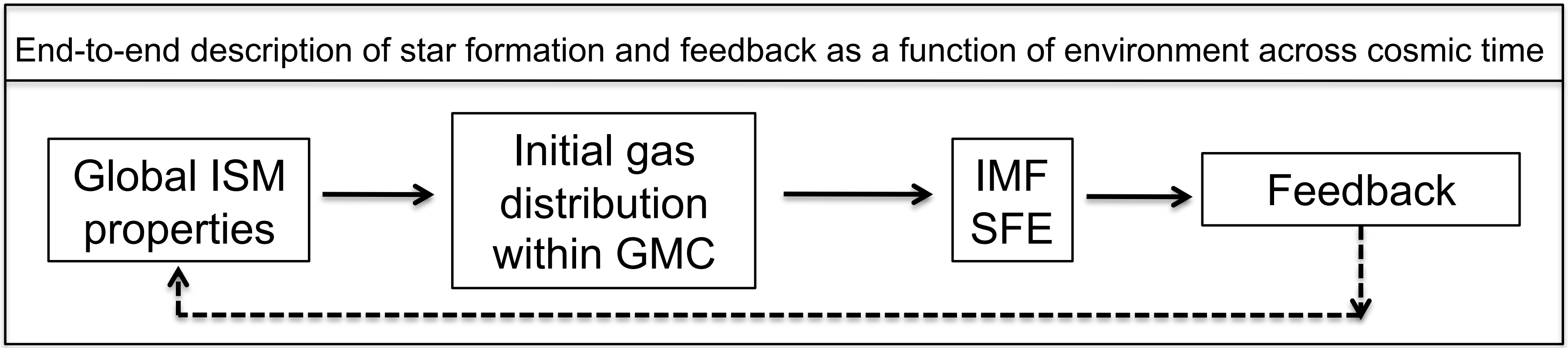


Tacconi+13



Madau & Dickinson 14

Recent progress in the field: observations



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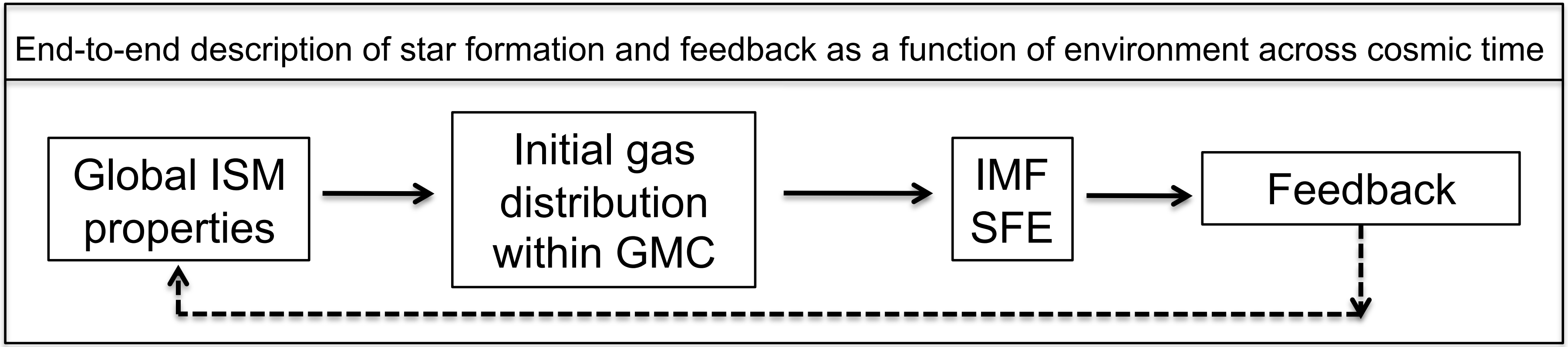


Identified observational counter parts

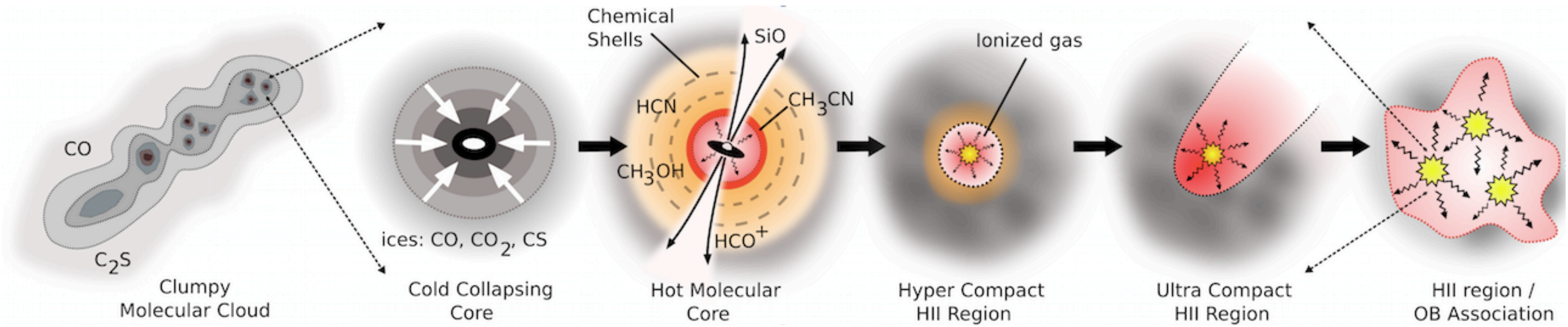
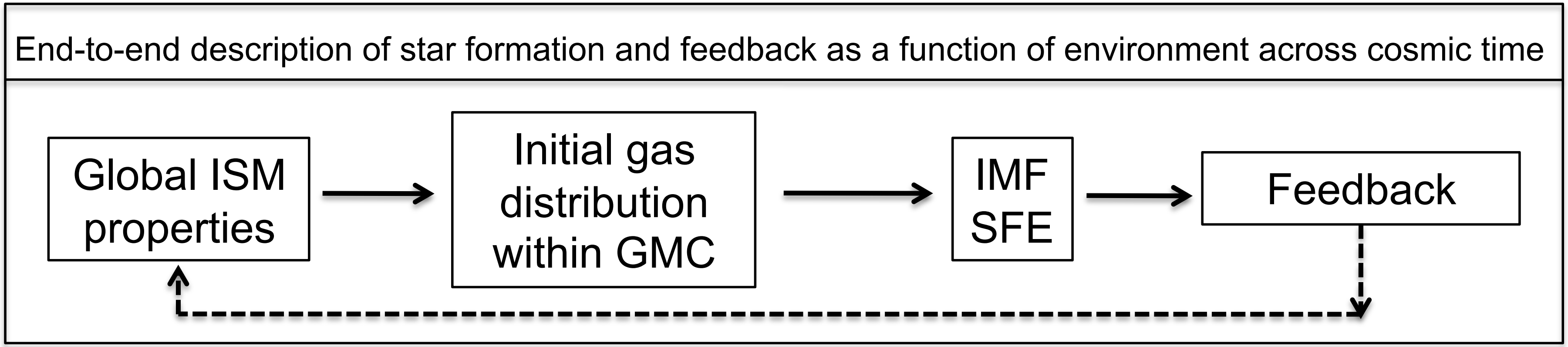


Image credit: Cormac Purcell

Recent progress in the field: observations



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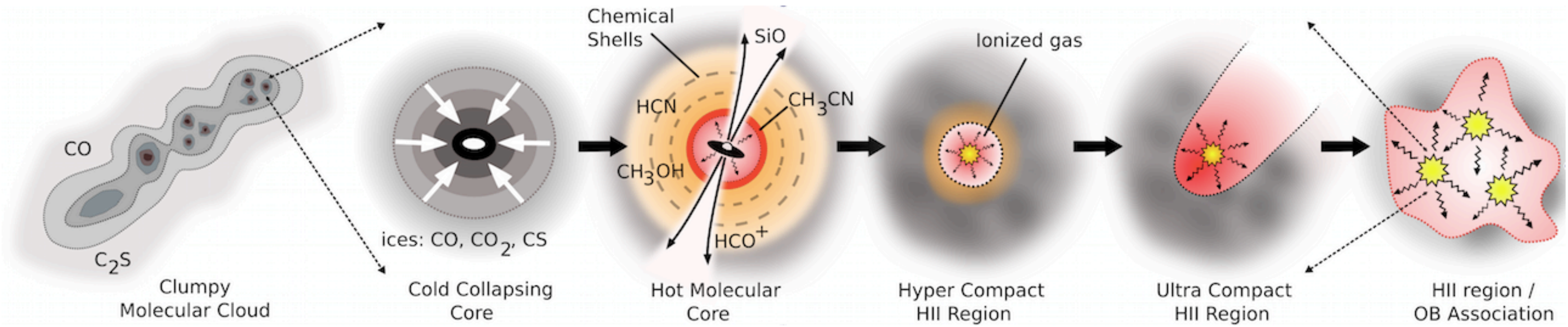
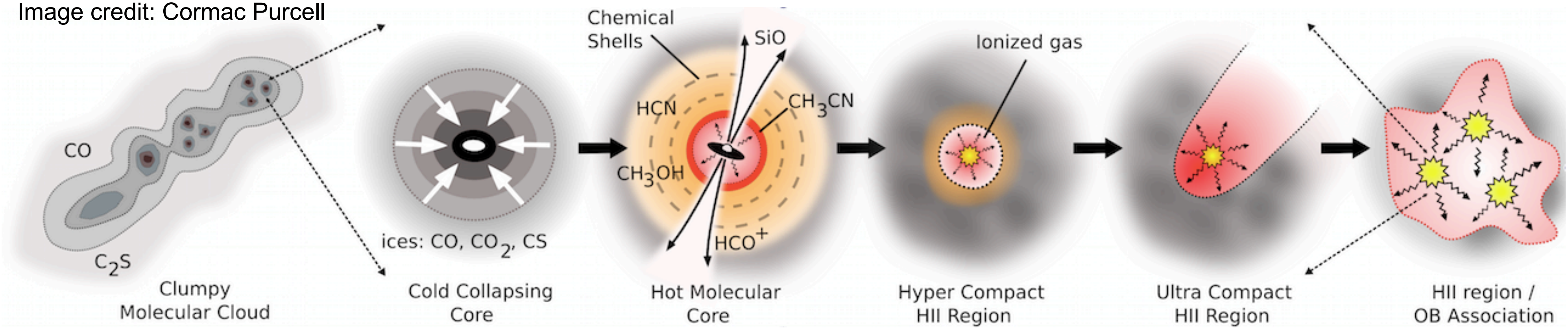


Image credit: Cormac Purcell

Deriving physical properties → boundary conditions for theory

Recent progress in the field: observations

Image credit: Cormac Purcell



Recent progress in the field: observations

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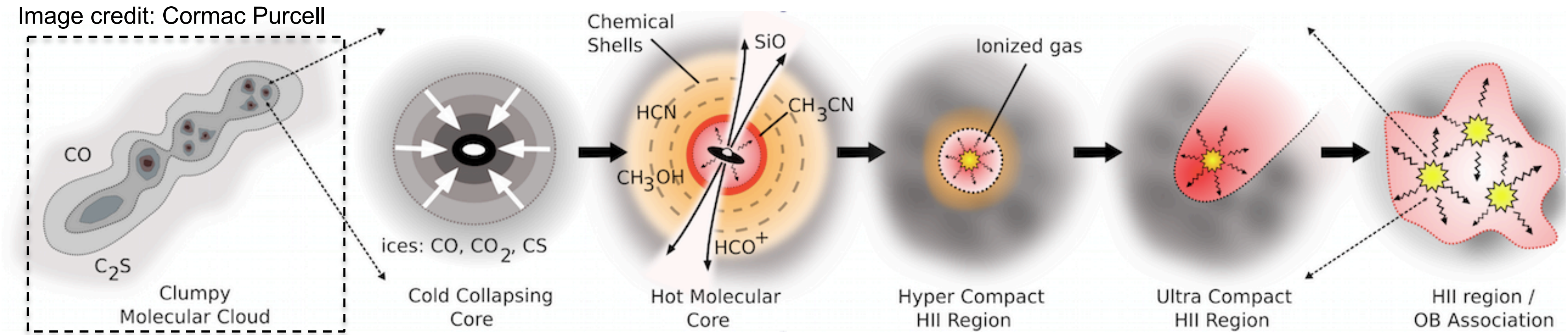


Massive star nurseries

$M(r) > 870\ r_{pc}^{4/3}\ M_{sun}$

$\Sigma \sim 1$ g.cm^{-2}, $n \sim 10^4$ cm^{-3}

$\sigma \sim 0.2 - 2$km/s

$B_{max} \sim 0.44(n_H/10^5\ \mathrm{cm}^{-3})^{0.65}$ mG

High (surface) density

Supersonic turbulence.

Often filamentary.

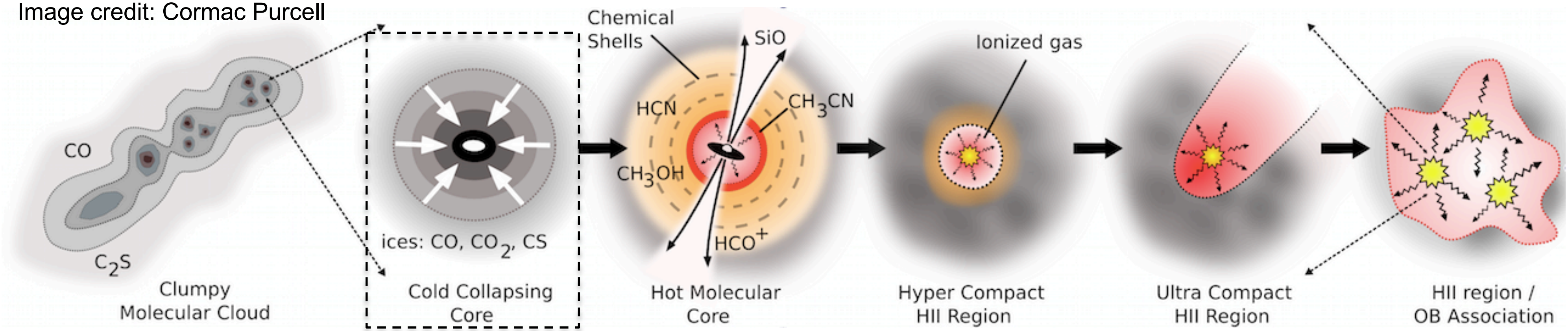
Complex kinematics
(merging of filaments?)

High deuteration and CO freeze-out

Pillai+06; Rathborne+06; Ragan+09,12; Kainulainen & Tan 13; Tan+13; Peretto+10; Henning+10; Beuther+10; Battersby+11, 14a,b; Butler & Tan 09,12; Peretto & Fuller 09; Kauffmann & Pillai 13a,b,c; Henshaw+13; Jimenez-Serra+10; Fontani+11,12; Beuther & Schilke 04; Rodon+12; Clark+07; Wang+08; Sakai+08; Charia+13; Li+14; Falgarone+08; Crutcher 12

Recent progress in the field: observations

Image credit: Cormac Purcell



Massive pre-stellar cores

General Properties

$n \sim 10^6$ cm^{-3}

$r_c \sim 0.1$pc

$\rho \propto r^{-k1}$, $1.1 < k1 < 1.6$

$dN/dM \propto M^{-k2}$, $1.7 < k2 < 2.1$

$0.3 < \alpha_{VIR} < 1.9$

Highly deuterated cold-core chemistry

Search for massive "monolithic" cores

Several massive (60 M_{sun}), compact (0.05pc) cores containing ~100 M_J with very little signs of star formation have been identified. Fragmentation prohibited? Strong B field?

Zhang+09; Pillai+11; Tan+13; Palau+11,14; Sanchez-Monge+13a.b; Caselli+99, Ceccarelli+14; Hernandez+12; Fontani+12; Chen+11; Mietinen+11; Sakai+12; Ragan+09; Beuther & Schilke 04; Bontemps+10; Duarte-Cabral+13; Cyganowski+14; Beuther+10; Tang+09; Sridharan+14; Girart+09;

Recent progress in the field: observations

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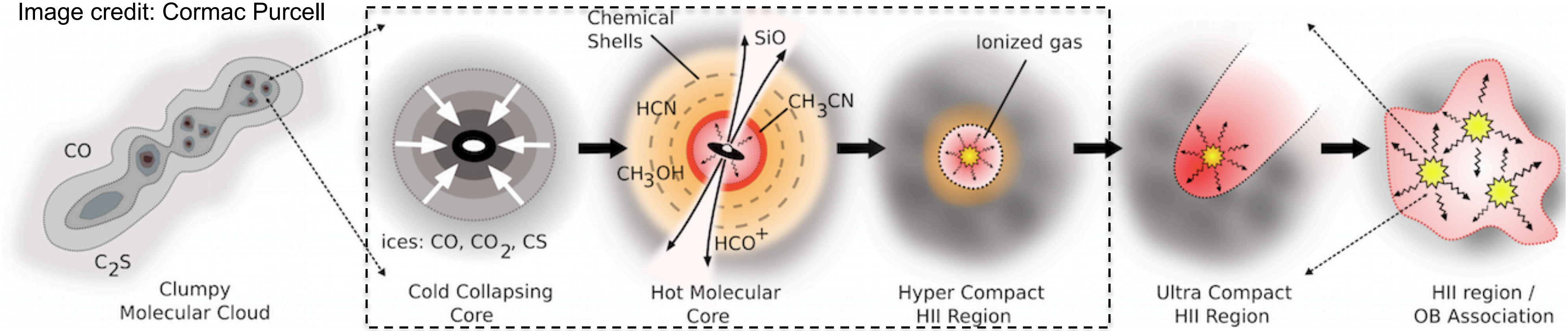

Accretion

Cloud (~pc) → Core (0.05pc); $10^{-4} < dM/dt < 10^{-1}\ M_{sun}/yr$

Core (0.05pc) → Disk (1000AU); $10^{-3} < dM/dt < 10^{-3}\ M_{sun}/yr$

Disk (1000AU) → Star; ?? < dM/dt < ??

Ionised accretion flows where $v_{esc} > c_{HII}$

Where are disks around O stars?

~10 rotating toroids around B stars

NIR/MIR interf.: 100AU compact sources (disks or outflows?)

NIR Spect: AU-scale kin. consistent with Keplerian rotation

Wu & Evans 03; Wu+05; Fuller+05; Barnes+10,11; Chen+10; Lopez-Sepulcre+10: Schneider+10; Klaassen+12; Peretto+13; Lumsden+11, Keto+02; Sollins+05; Beltran+06; Zapata+08; Wu+09; Girart+09; Beuther+13; Wyrowski+12; Goddi+11; Chini+04; Preibisch+11; Kraus+10; de Wit+11; Boley+13; Cesaroni+05,07; Beltran+11; Wang+12; Sanchez-Monge+13; Zhang13; Franco-Hernandez+09; Fernandez-Lopez+11; Carrasco-Gonzalez+12; Bik &Thi 04; Davies+10; Ilee+13;

Recent progress in the field: observations

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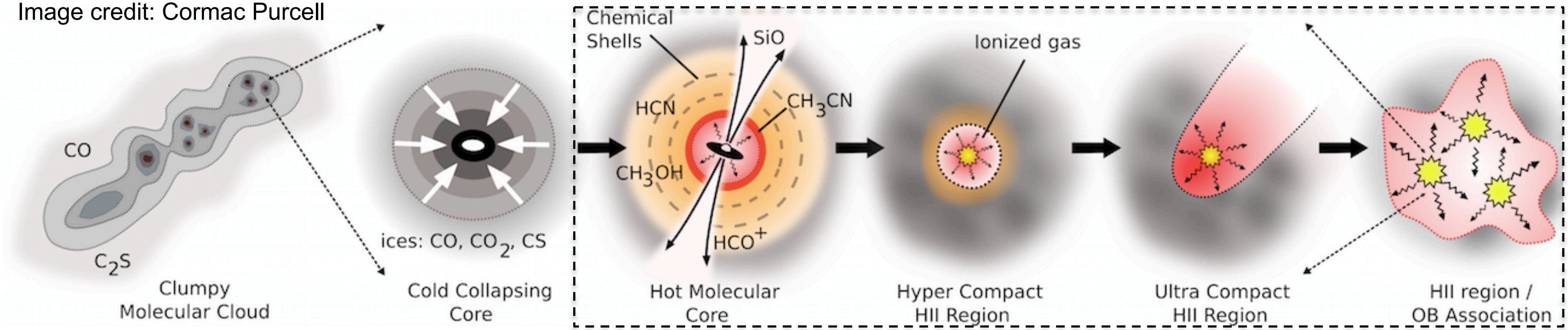


Outflows

P_{out}, F_{out}, $dM_{out}/dt \propto L$ for $0.1 < L < 10^6 L_{sun}$

Outflow collimation ↓ as M_* ↑

SiO jets → same collimation as low mass stars

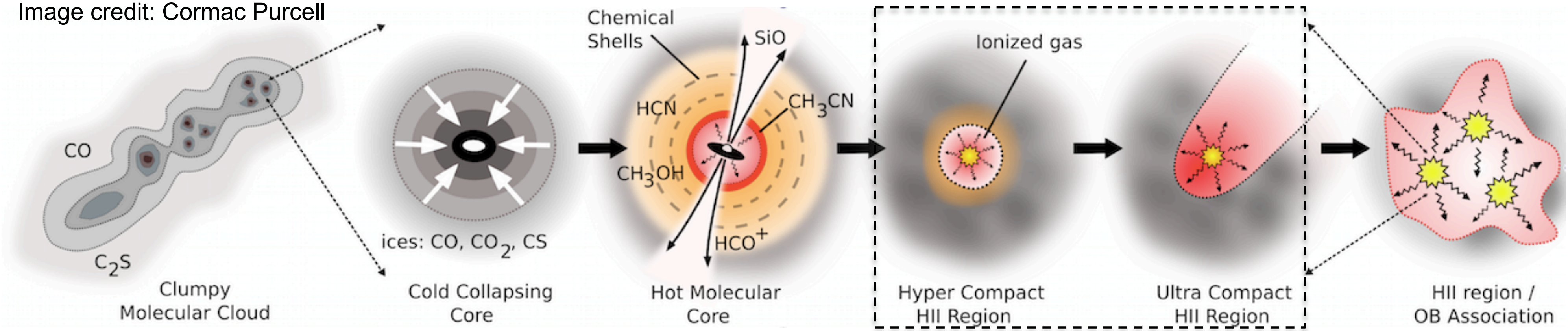
Explosive outflows → dynamic (ejection?) event few hundred years ago

Are the observed scaling relations between outflows and mass/ luminosity evidence for similar mechanism across full mass range? How important are dynamic encounters?

Beuther+02; Wu+05; Garay+07; Lopez-Sepulcre+09,11; Beuther & Shephard 05; Vaidya+11; Zhang+14; Sanchez-Monge+13; Hunter+99, Qiu+07,12; Zhang+07; Codella+13; Leurini+13; Sollins+04; Greenhill+13; Cesaroni+13; Allen & Burton 93; Bally+11; Zapata+13; Tan 04; Bally & Zinnecker 05; Goddi+11; Bally+11;

Recent progress in the field: observations

Image credit: Cormac Purcell



Ultra-compact (UC) and Hyper-compact (HC) HII regions

General Properties

$T \sim 10^4$ K

$r_{UC} < 0.1$pc, $r_{HC} < 0.1$pc

$\sigma_{HC} \sim 40$ km/s

Ionised accretion + outflows

HII regions lifetimes

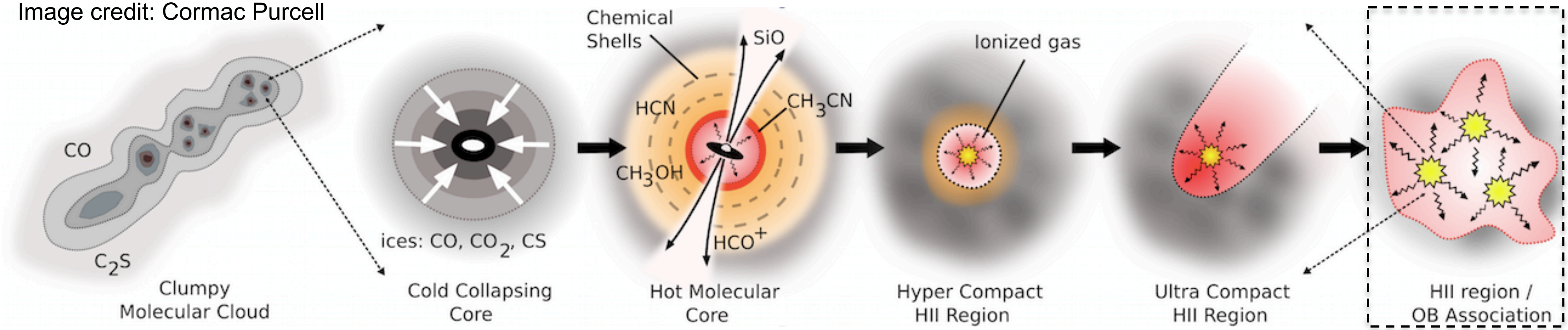
$t_{RQ} \sim 5 \times 10^5$ yr ; $L \sim 1 \times 10^4\ L_{sun}$
$t_{RQ} \sim 1 \times 10^5$ yr ; $L \sim 5 \times 10^4\ L_{sun}$
$t_{RQ} \sim 0$ yr ; $L \sim 1 \times 10^5\ L_{sun}$

$t_{HII} >> t_{expansion}$ → confinement? replenishment?

Wood & Churchwell 89; Beuther+07; Hoare+07; Sewillo+11; Lumsden+12, 13; Mottram+11; Keto 02,07; Keto & Klaassen 08; Ginsburg+14

Recent progress in the field: observations

Image credit: Cormac Purcell

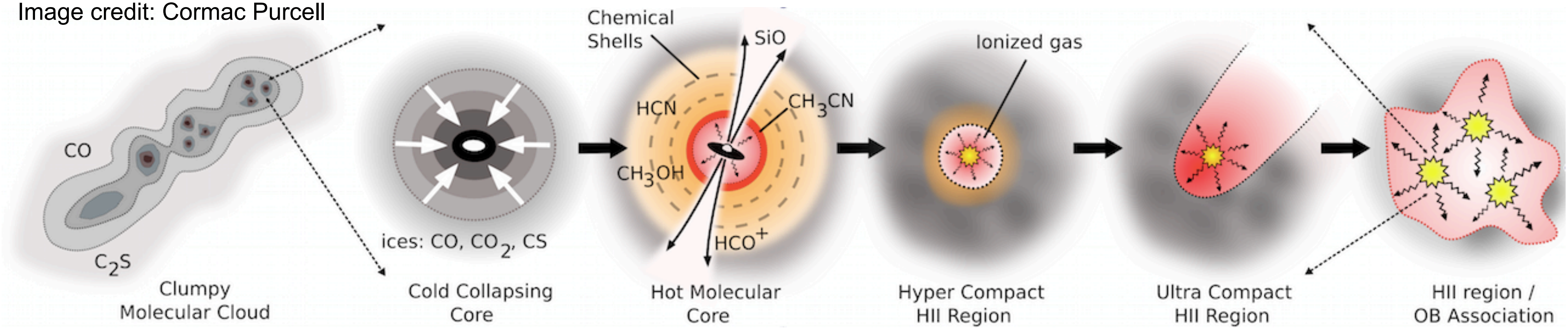


Young, massive stellar populations
Mass segregated → consensus this is dynamic in origin, not primordial IMF Universal Evidence that small fraction of O stars may have formed in "isolation" Upper mass limit? 150Msun? 300Msun? No "popping" clusters

Wright+14,15; Bastian+10; Bressert+12; de Wit+04; Figer+05; Crowther+12

Recent progress in the field: observations

Image credit: Cormac Purcell



Distances!

Crucial for measurements of mass, luminosity, …

Kinematic distances uncertain to tens of percent

Parallax measurements accurate to percent level but observationally difficult and time consuming

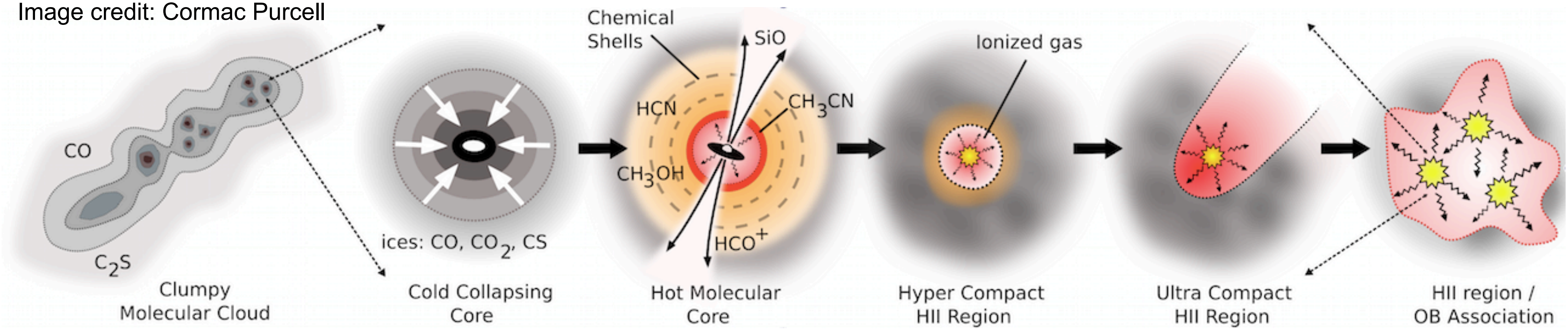
VLBA large program: Reid, Menten, Brunthaler, Immer, …

Talk outline

- Fundamental barriers to progress
- Recent progress in the field: theory
- Major open questions
- Recent progress in the field: observations
- Looking forward to 2020s (and beyond)

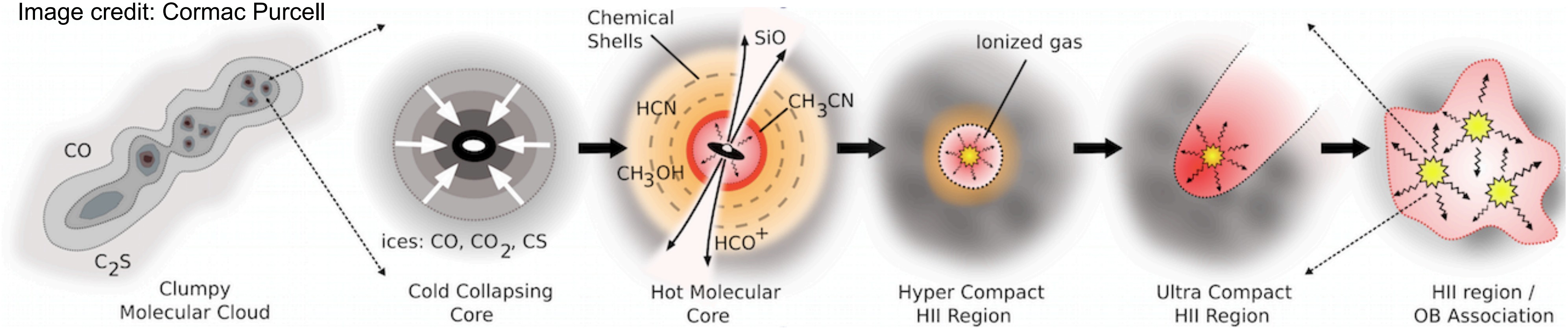
Looking forward to 2020s (and beyond)

Image credit: Cormac Purcell



Looking forward to 2020s (and beyond)

Image credit: Cormac Purcell



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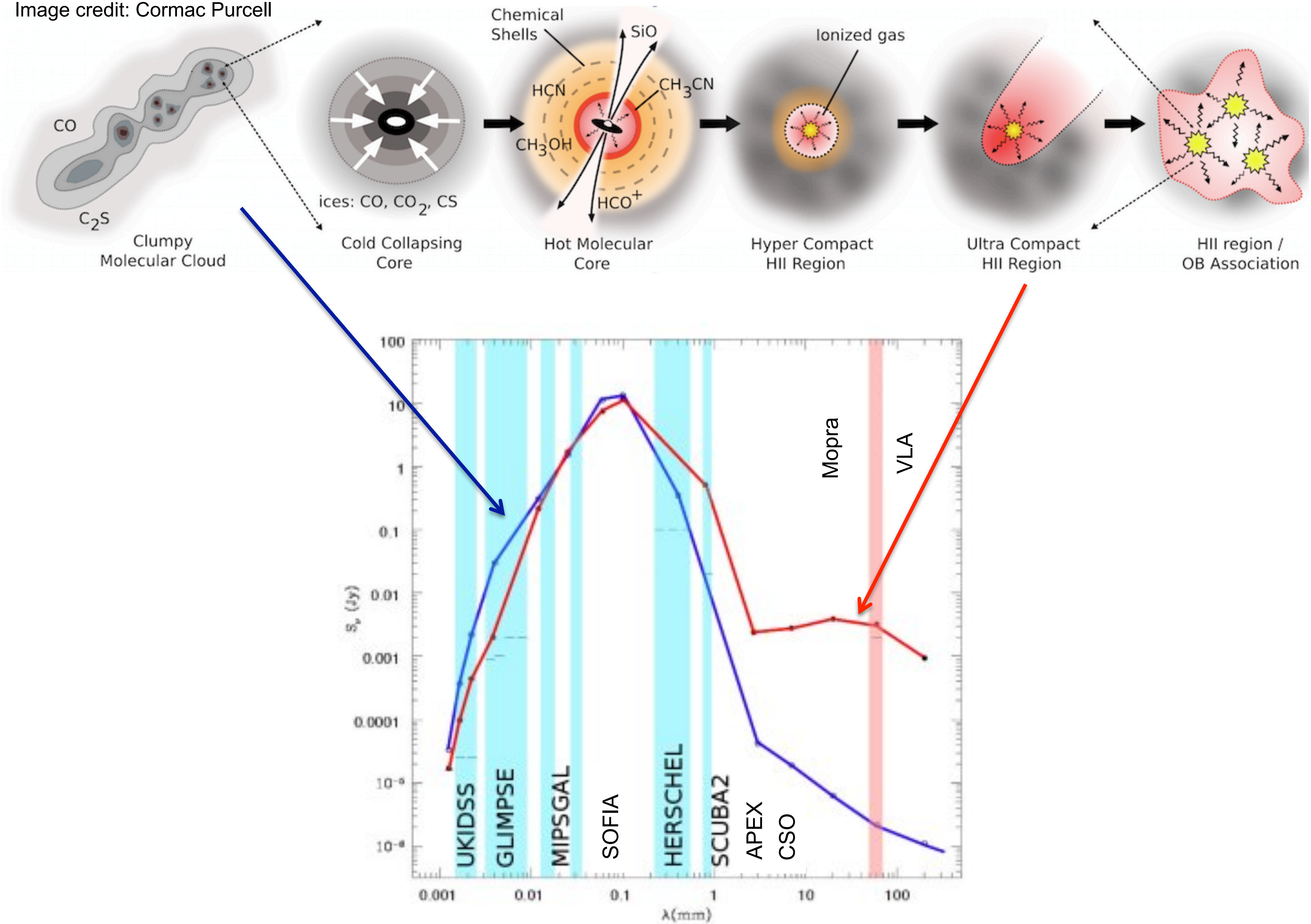
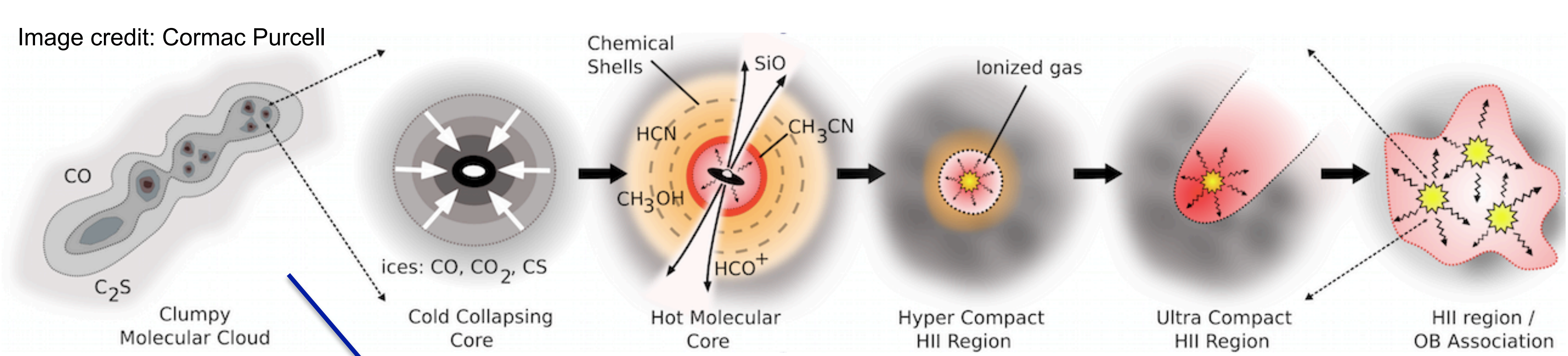




Access to large-area survey instruments from micron to cm wavelengths

+

Enormous effort by Galactic star formation community

=

Mapped most of Galactic plane at <20-30” resolution

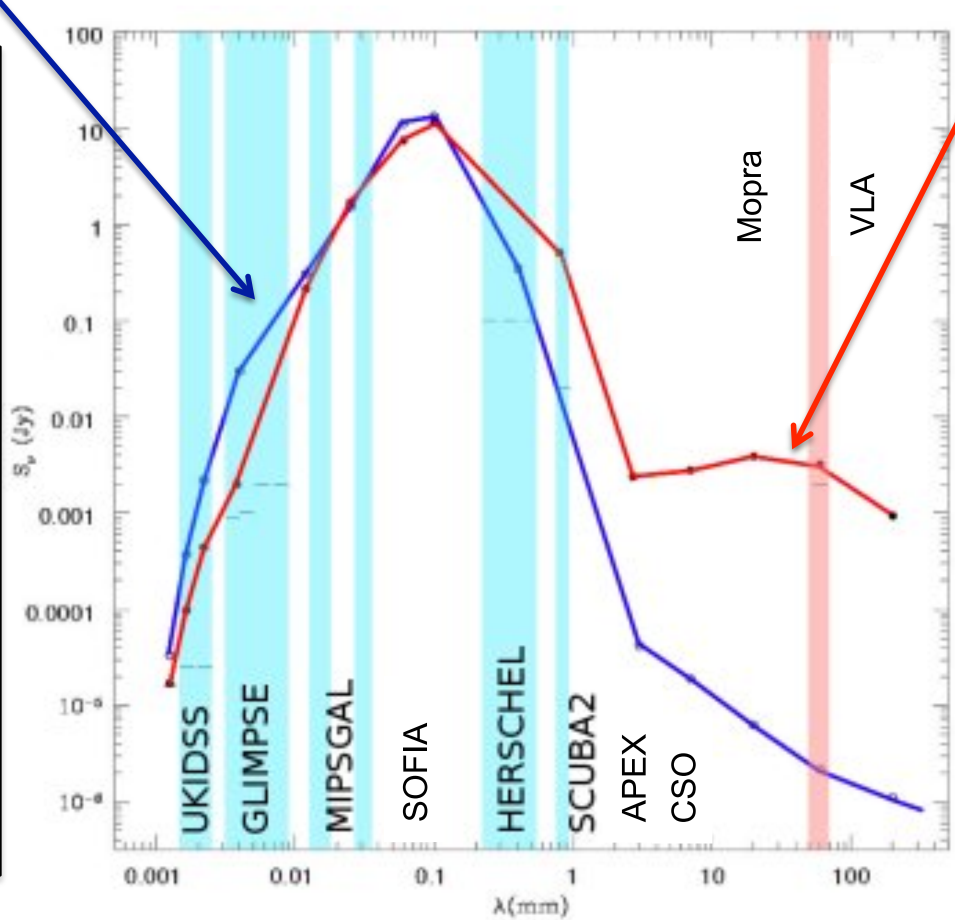
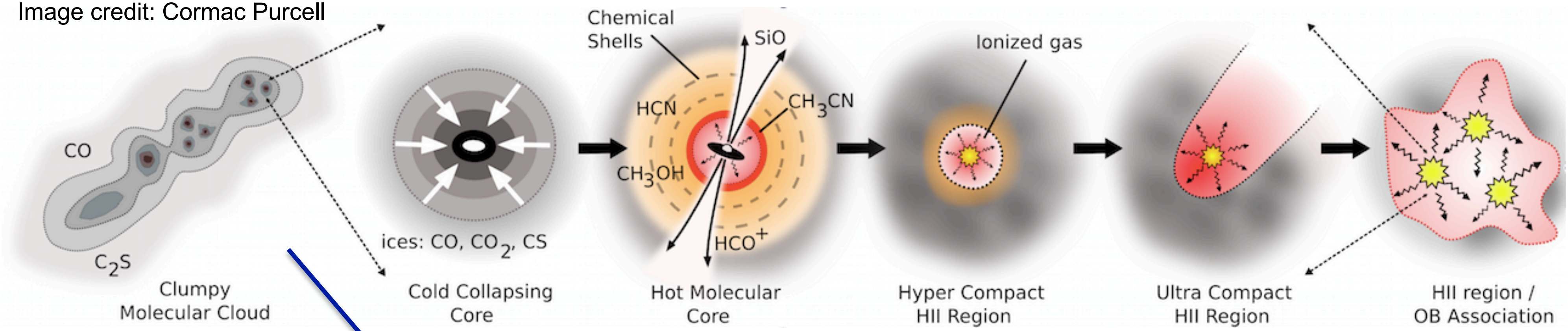


Image credit: Cormac Purcell



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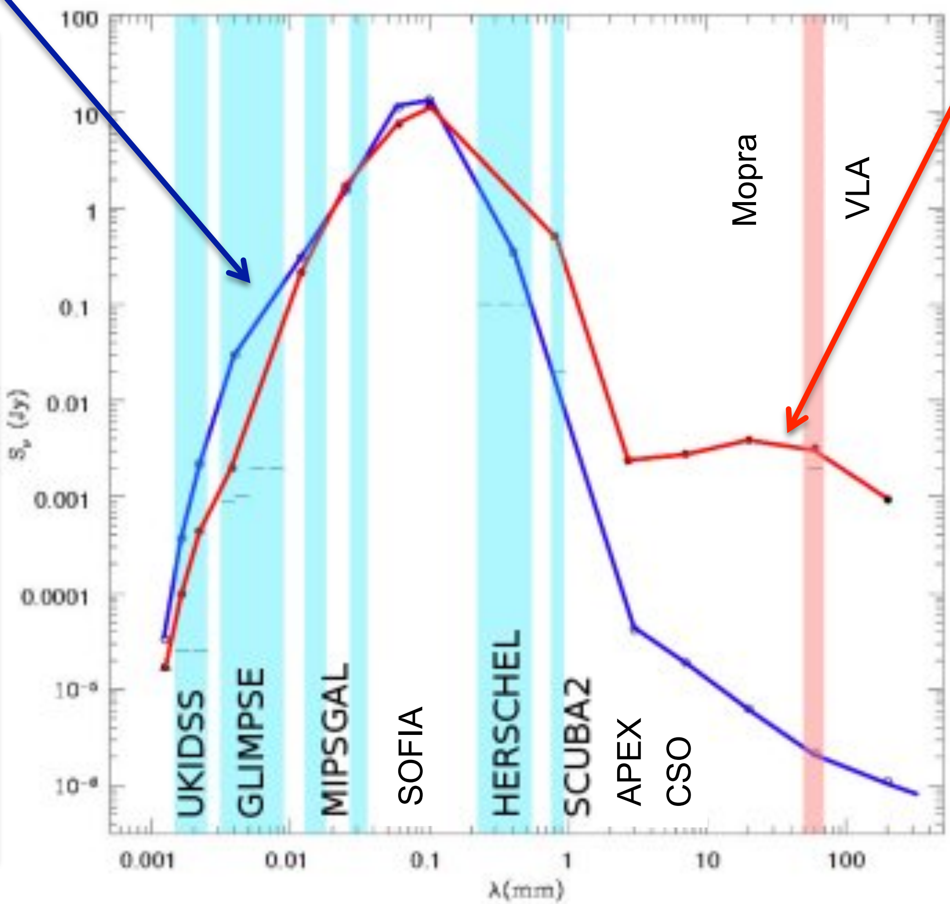


Spectral energy distribution

+

Association with other SF activity tracers

+

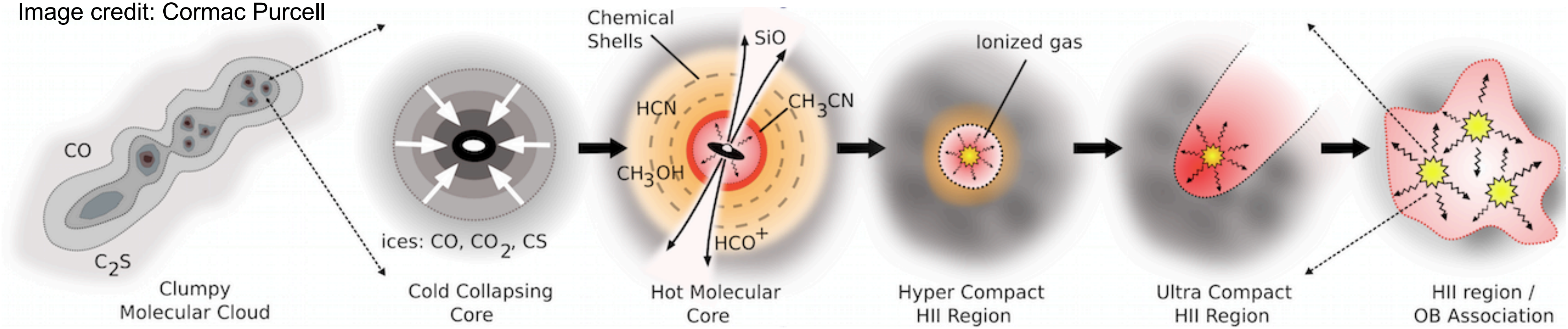
Chemistry

=

Rough categorization of regions by relative age

Looking forward to 2020s (and beyond)

Image credit: Cormac Purcell



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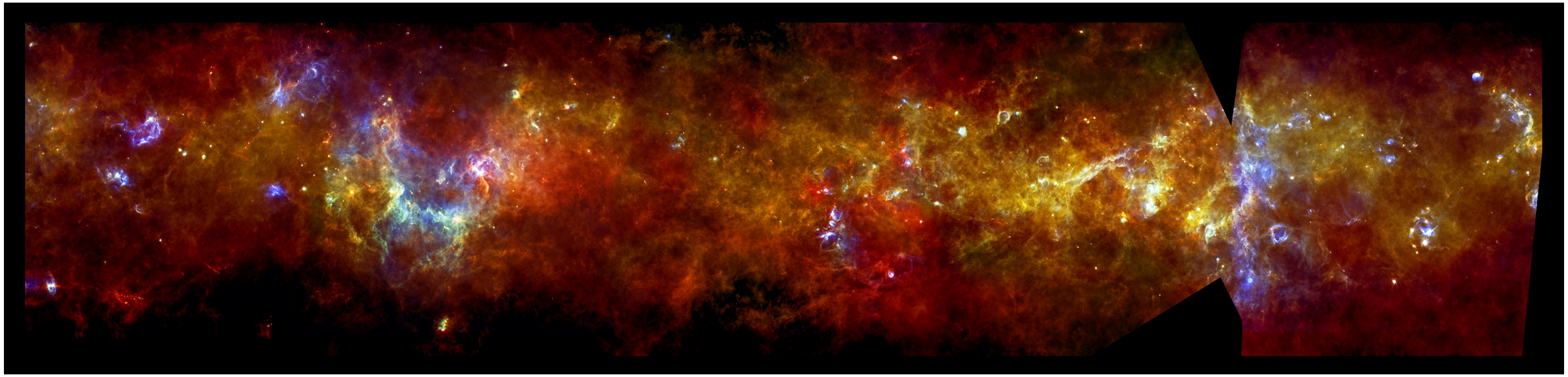
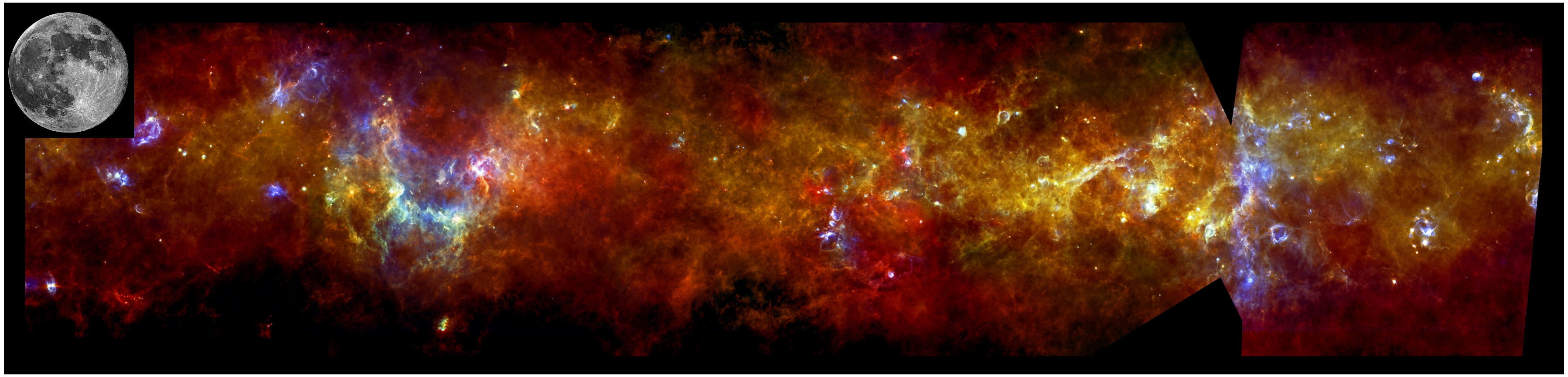
12 degrees of the Galactic Plane = 1/30th of total longitude extent



HiGAL (PI Molinari): 70, 160, 250, 350, 500μm

12 degrees of the Galactic Plane = 1/30th of total longitude extent



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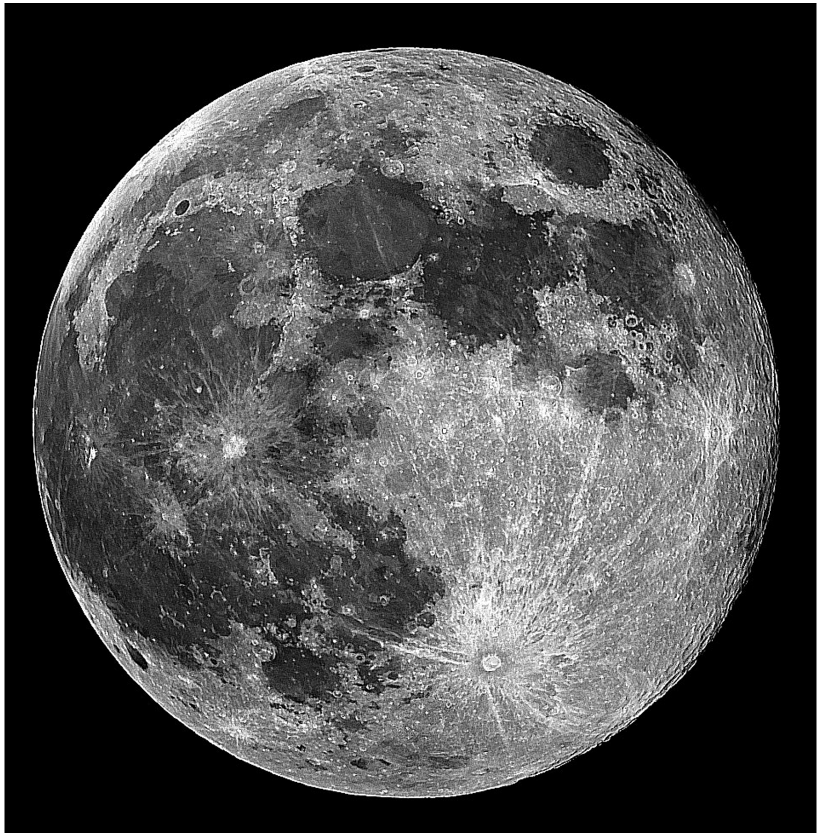

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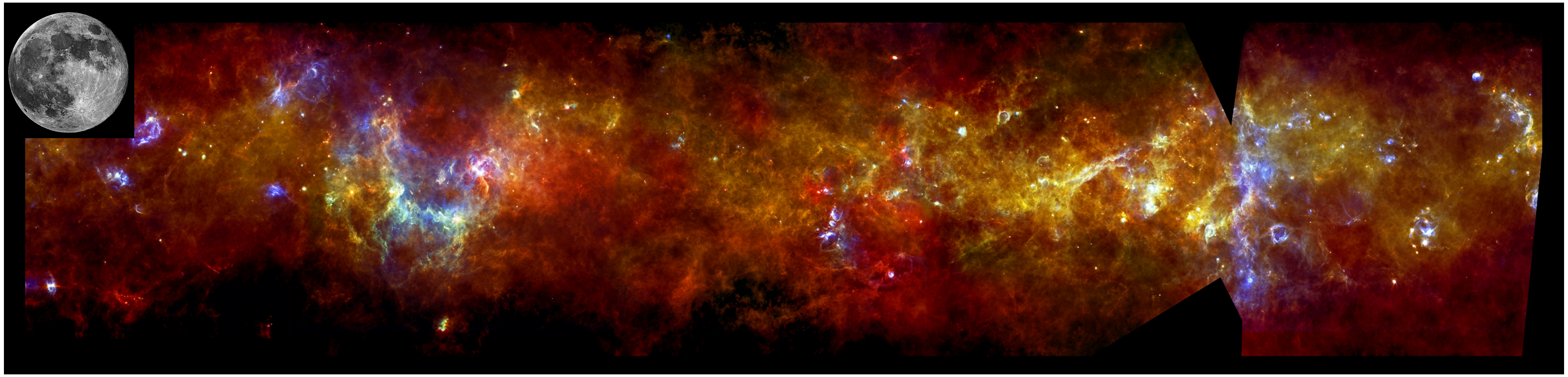

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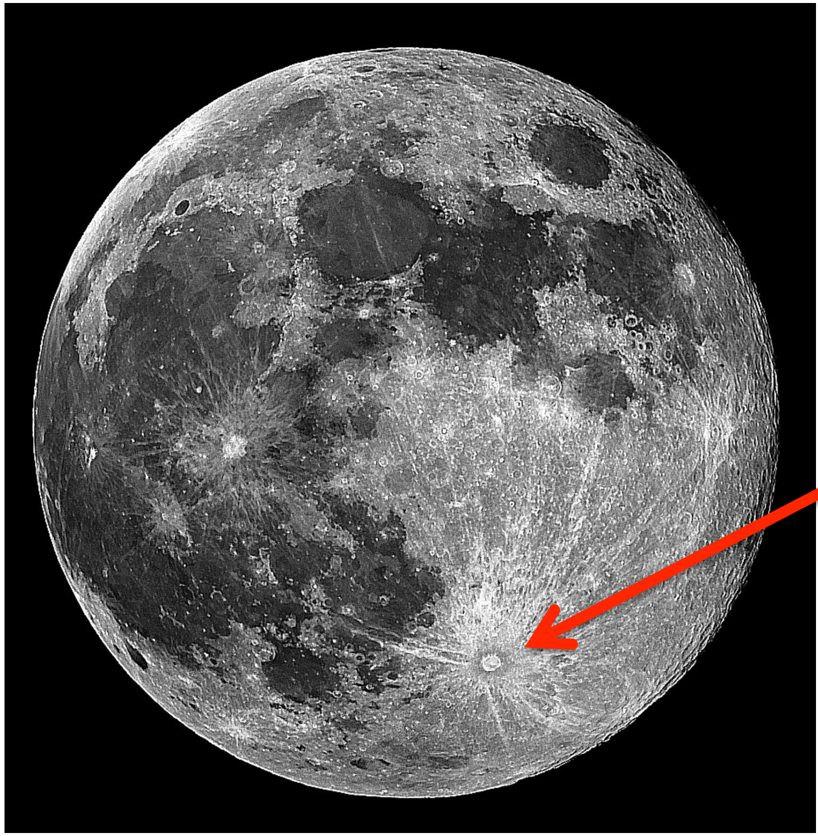
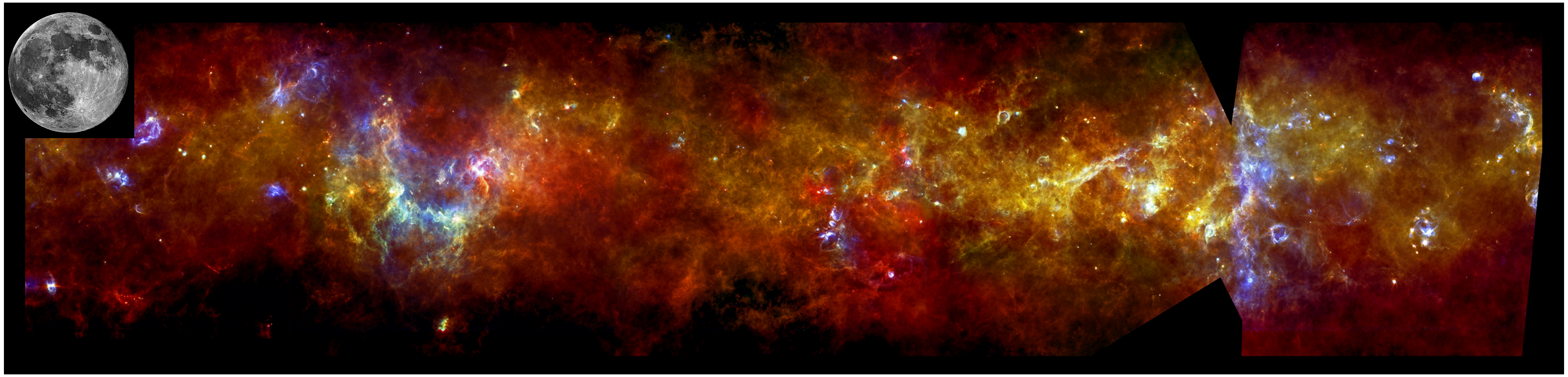


Crater = Maximum ALMA field of view
(at longest wavelength)

12 degrees of the Galactic Plane = 1/30th of total longitude extent



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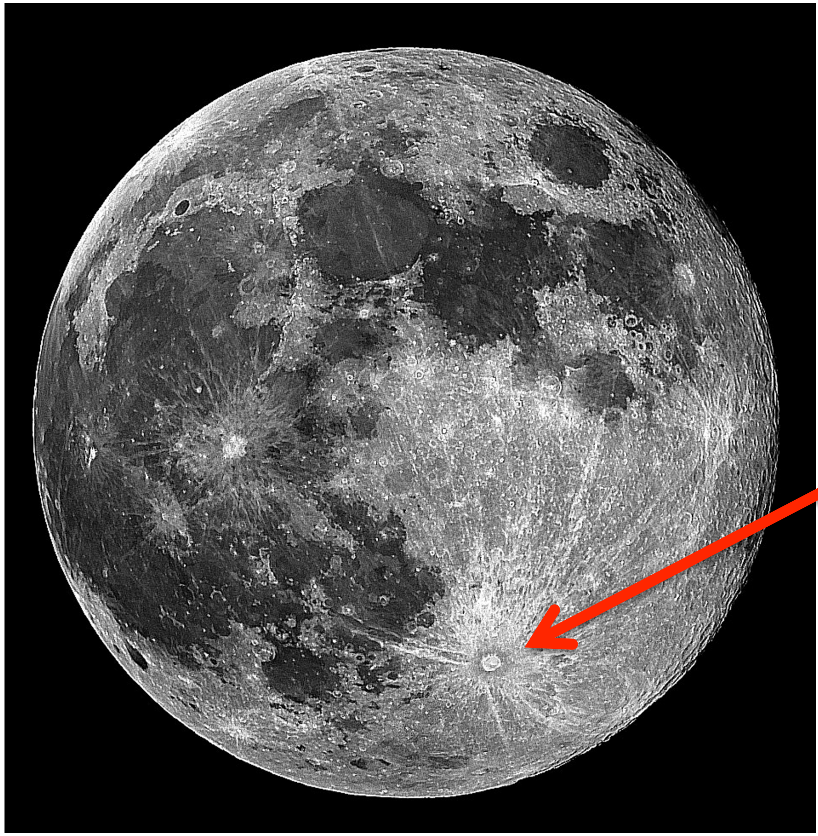
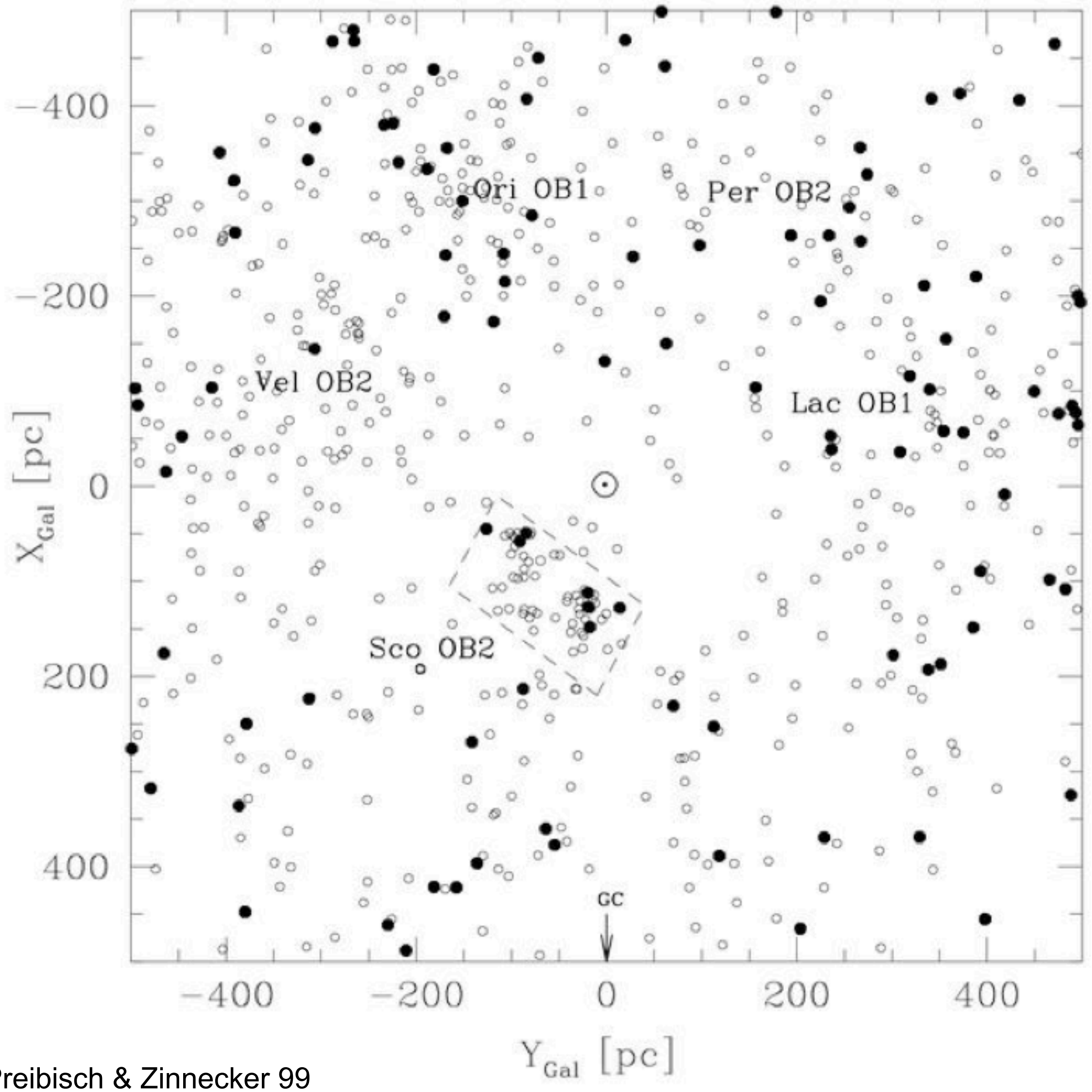


Crater = Maximum ALMA field of view
(at longest wavelength)

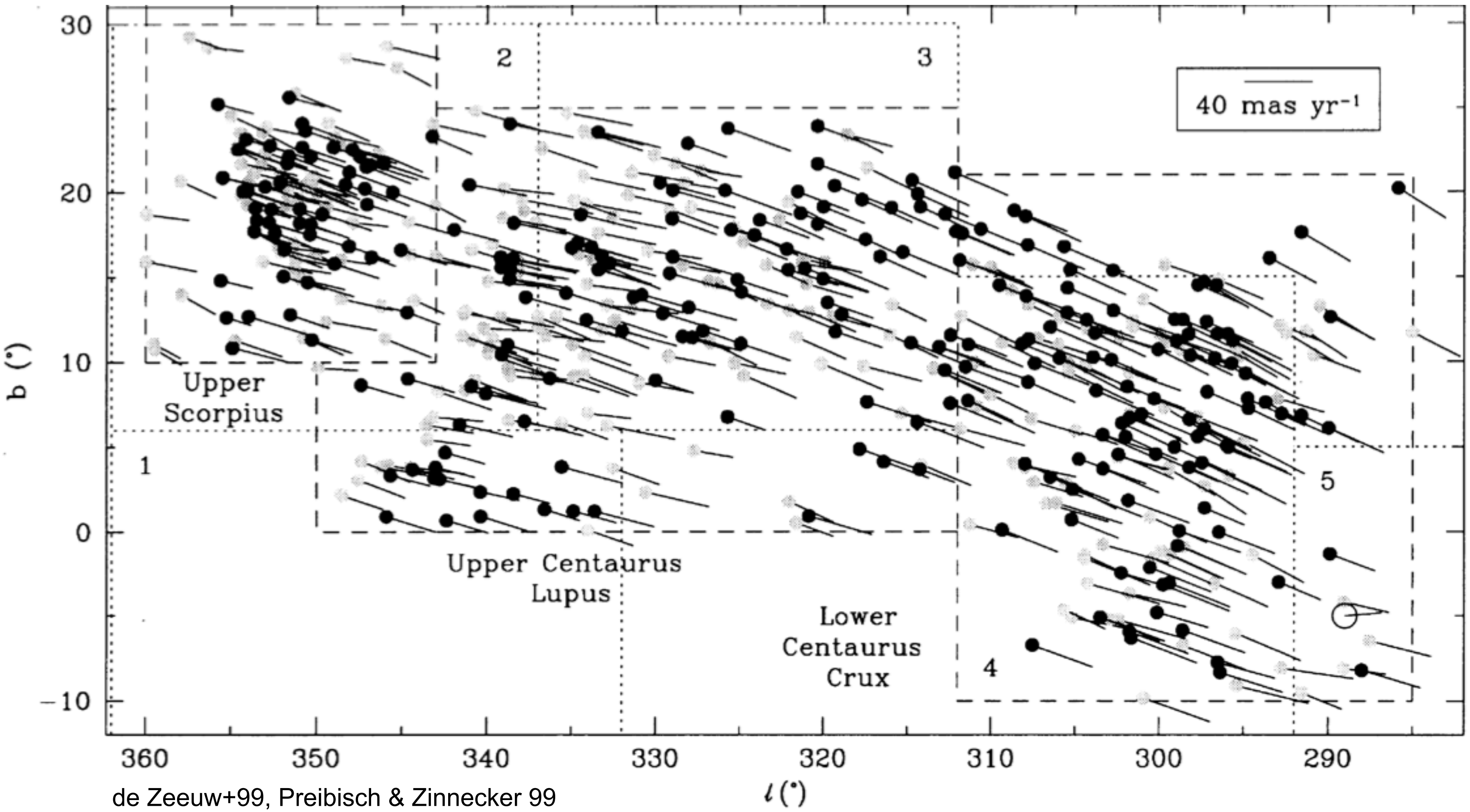
Need wide-field 5” resolution surveys to find high mass cores in GMCs.

Most local SF in associations, not clusters



de Zeeuw+99, Preibisch & Zinnecker 99

“Associations are nasty!”*

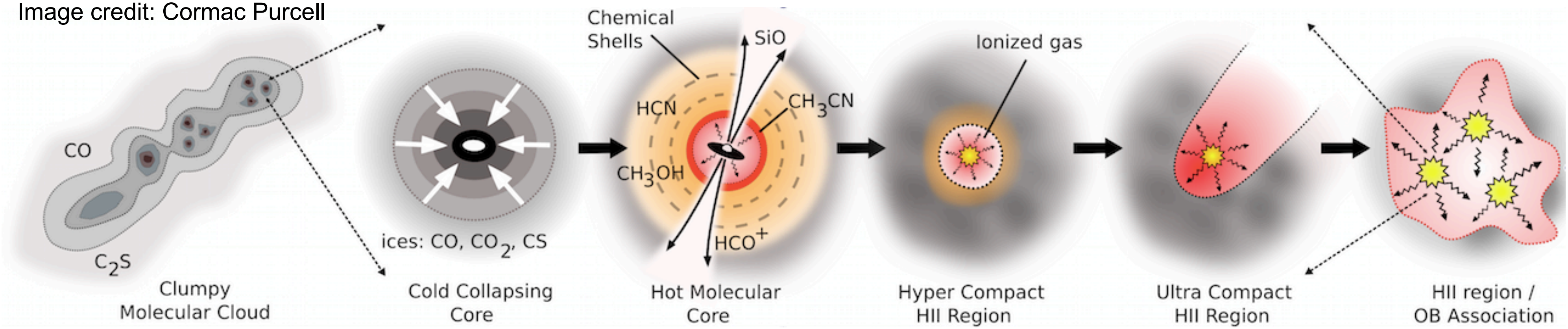


de Zeeuw+99, Preibisch & Zinnecker 99
Preibisch & Mamajek 07

*Simon Goodwinn @ RAS meeting 9/1/15: “Theory and Kinematics in the Gaia Era”

Looking forward to 2020s (and beyond)

Image credit: Cormac Purcell



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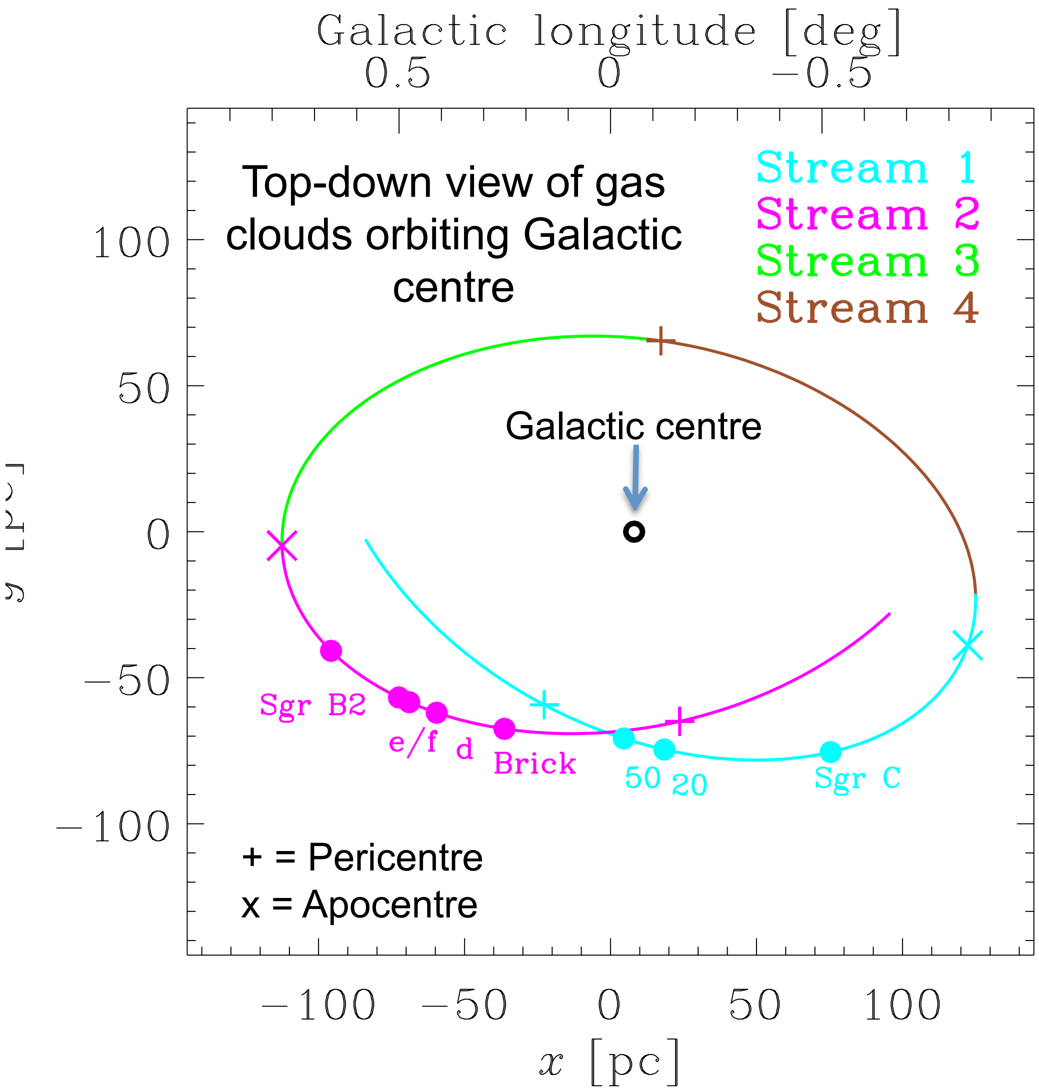
Time Machine: "Snapshots" to "Movies"



<u>Goal: overcome "snapshot" limitation</u>

Exploits circumnuclear gas ring orbiting ~100pc from Galactic centre

Gas on nearly elliptical orbit, moving clockwise around the Galactic centre

Gas at large distances from the Galactic centre is not forming stars

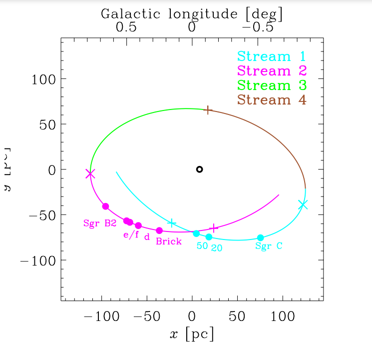
Gas past pericentre has progressively more star formation

Gas approaching pericentre with bottom of gravitational potential gets compressed, triggering star formation

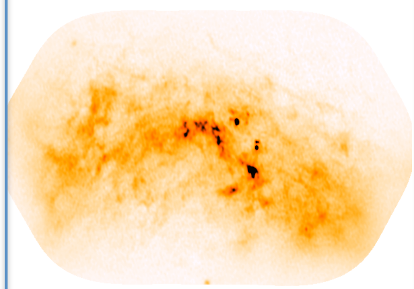
Longmore et al 2013b, MNRAS, 433, 15
Kruijssen, Dale & Longmore, MNRAS,

Time Machine: “Snapshots” to “Movies”

Time Machine 1

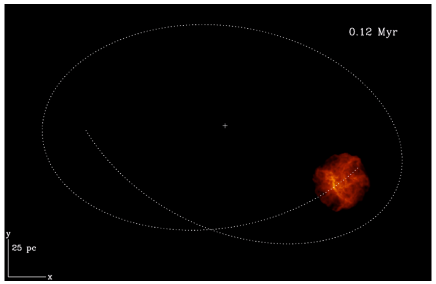


Orbital modelling



Observations

1. Initial conditions of gas cloud
2. Final stellar population
3. Mass of gas in gravitationally-bound, star-forming ‘cores’ as a function of ***absolute*** time since star formation began



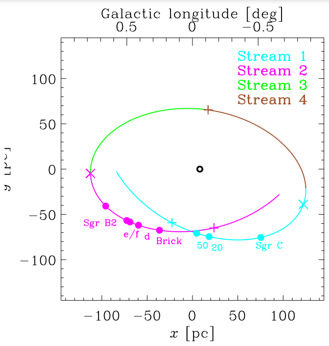
Simulations including different physics to test model predictions

Watch process of individual stellar mass assembly as a function of absolute time!

Longmore et al 2013b, MNRAS, 433, 15
Kruijssen, Dale & Longmore 2015, MNRAS,
Kruijssen, Dale & Longmore in prep

Time Machine: "Snapshots" to "Movies"

Time Machine 1



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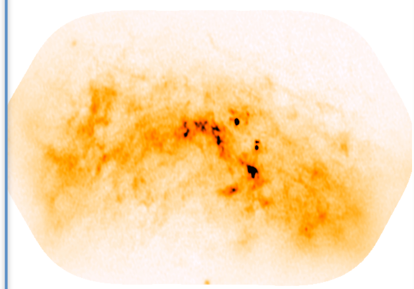

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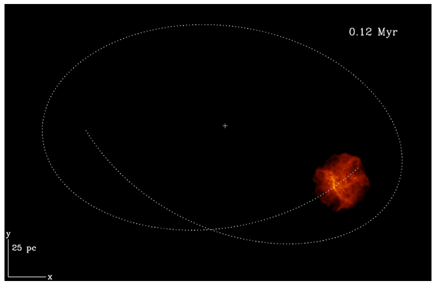


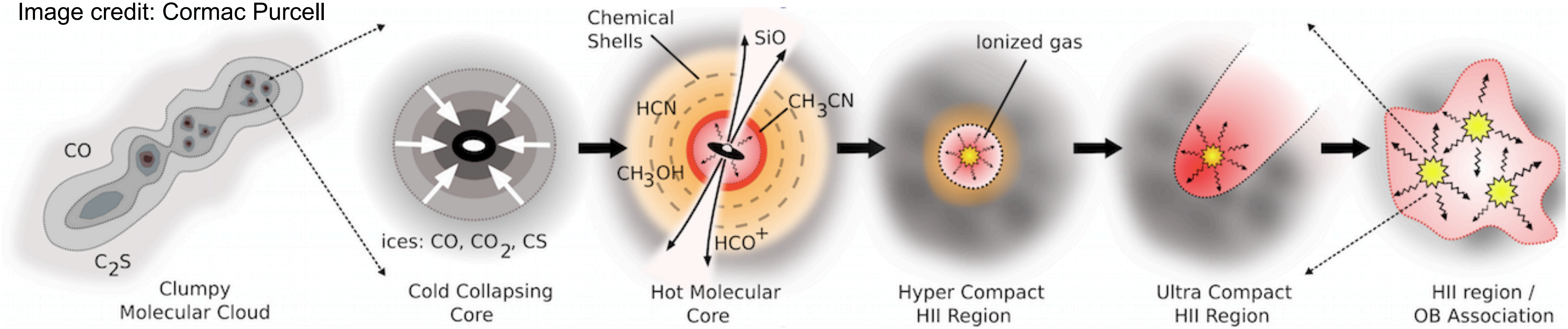
Simulations including different physics to test model predictions

Watch process of individual stellar mass assembly as a function of absolute time!

Solution to snapshot limitation

Looking forward to 2020s (and beyond)

Image credit: Cormac Purcell



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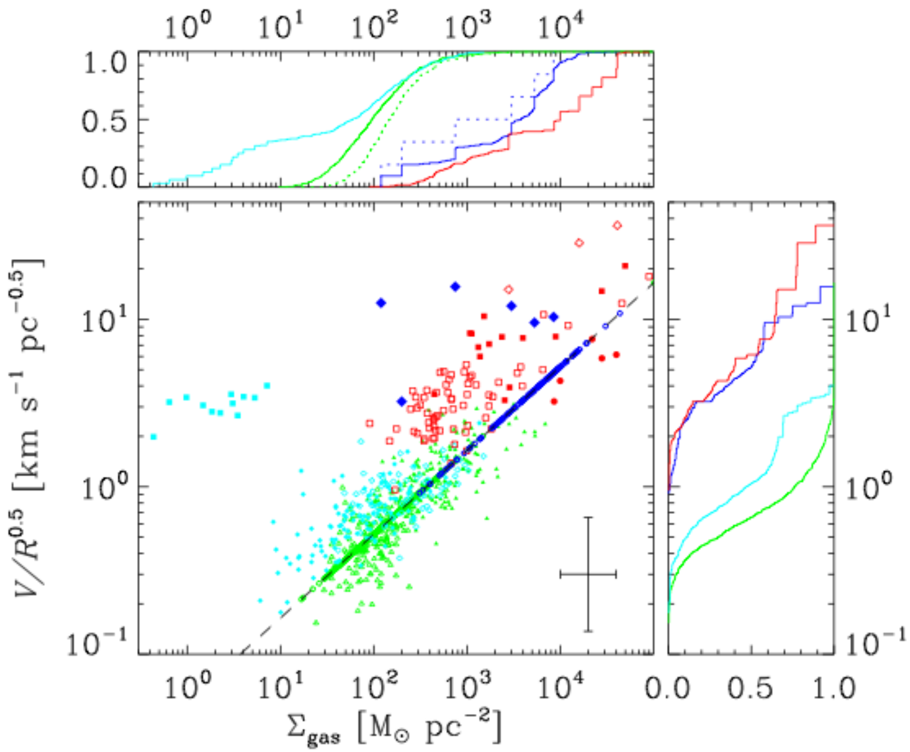
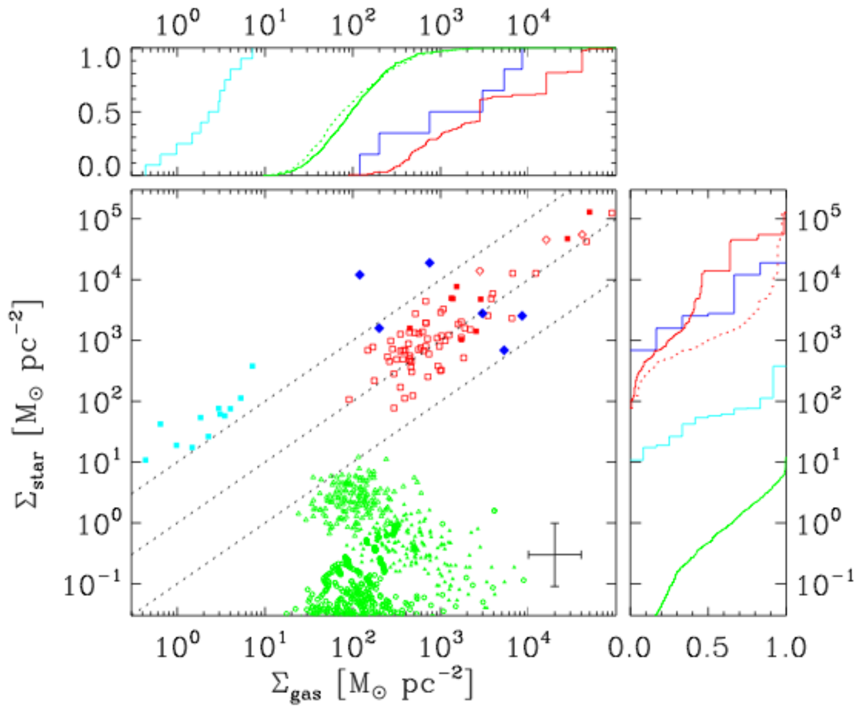
How similar is the gas in the Milky Way to other star formation environments across cosmological timescales?

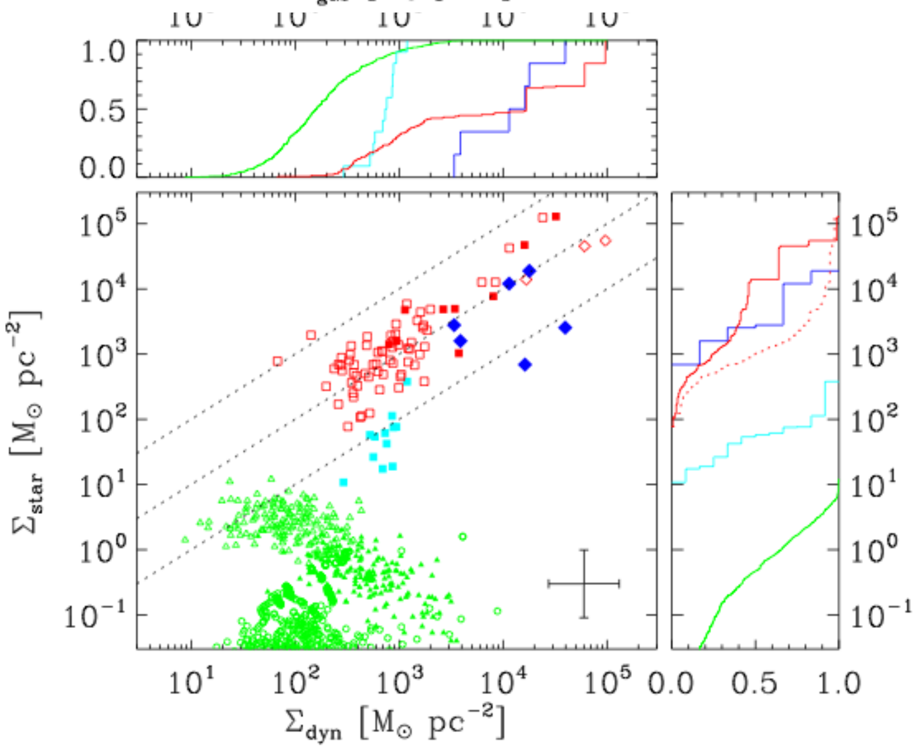
Kruijssen & Longmore 2013, MNRAS, 435, 2598

- Problems to overcome (many!)
  - Heterogeneous data sets
  - Different observational tracers
  - Large range in spatial resolution
- Approach
  - Identify properties that can be most robustly compared
    - Limited by most distant sources (high-z galaxies)
  - R, ΔV, M_{gas}, M_{star}
  - R, ΔV, Σ_{gas}, Σ_{star} (normalise by spatial area)
  - Break sample in to four groups
    - Disks of nearby spirals
    - Centre of the MW
    - Starburst systems
    - High-z galaxies

Plot everything against everything else and see if can find unique properties to separate gas in the groups





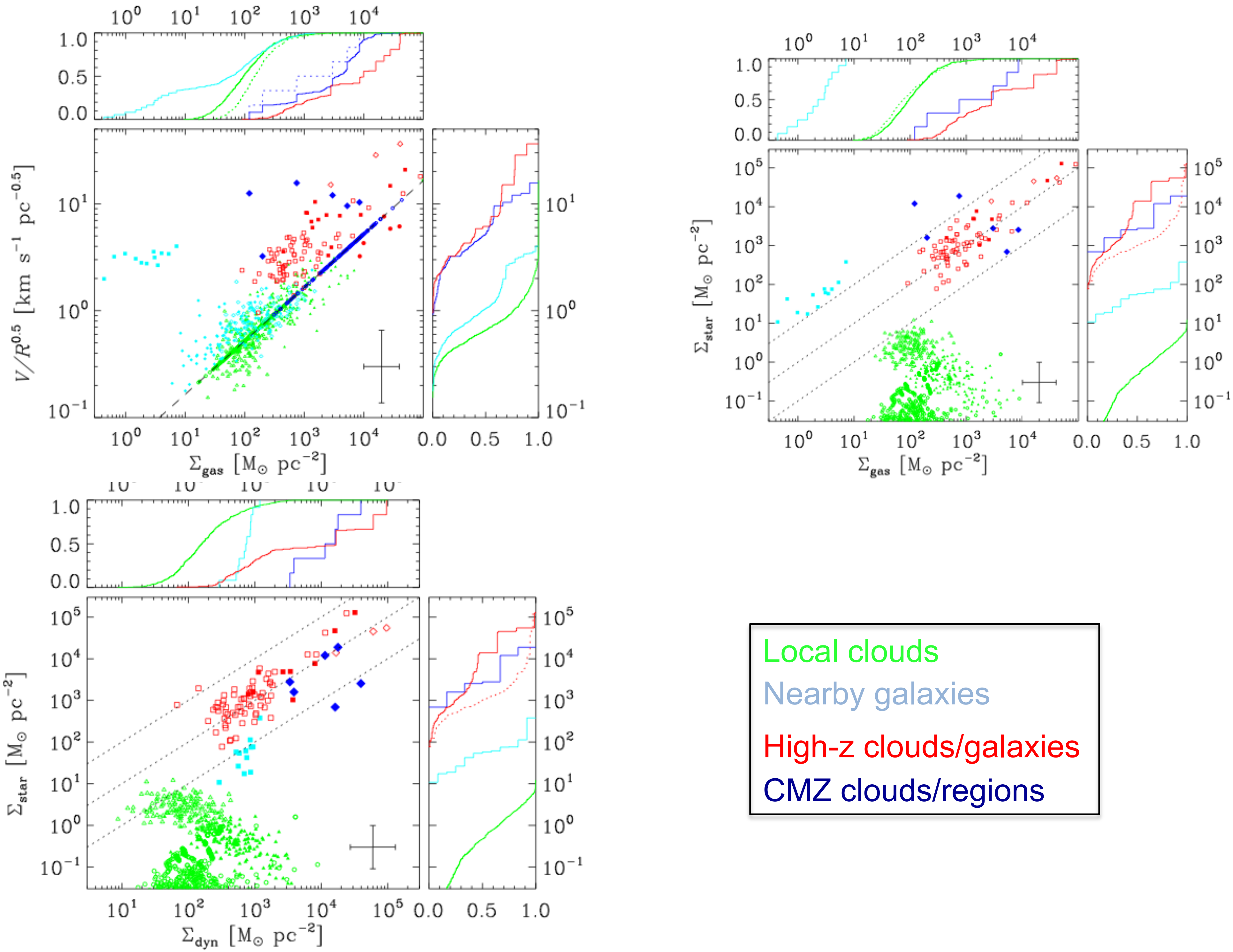


Local clouds?

Nearby galaxies?

High-z clouds/galaxies?

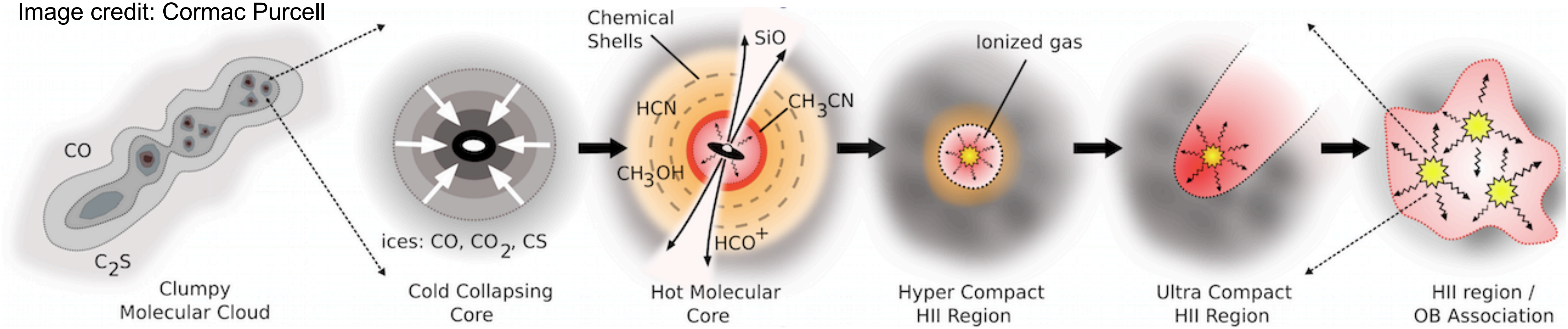
CMZ clouds/regions?



V/R^0.5 [km s^-1 pc^-0.5]
Σgas [M⊙ pc^-2]
Σstar [M⊙ pc^-2]
Σgas [M⊙ pc^-2]
Σstar [M⊙ pc^-2]
Σdyn [M⊙ pc^-2]
Local clouds
Nearby galaxies
High-z clouds/galaxies
CMZ clouds/regions

Looking forward to 2020s (and beyond)

Image credit: Cormac Purcell



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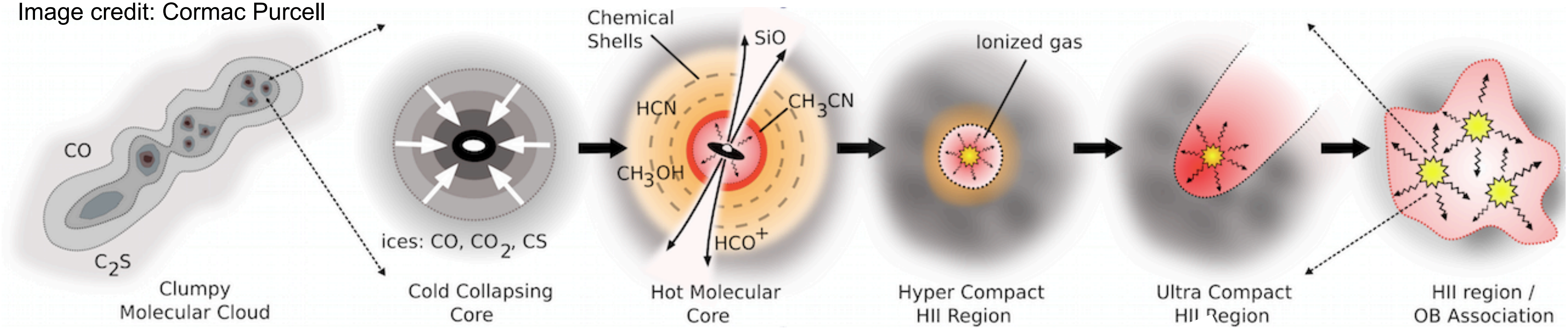


Towards an end-to-end description of star form... as a function of environment ac...

1. Identify all hi... ...w

2. Separat... ...nmental conditions

3. Measu... ...matic structure from stellar to GMC scales

4. ...ion of environment and compare to theory/simulations

5. Put in context of cosmic star formation

What is needed?

Report on the

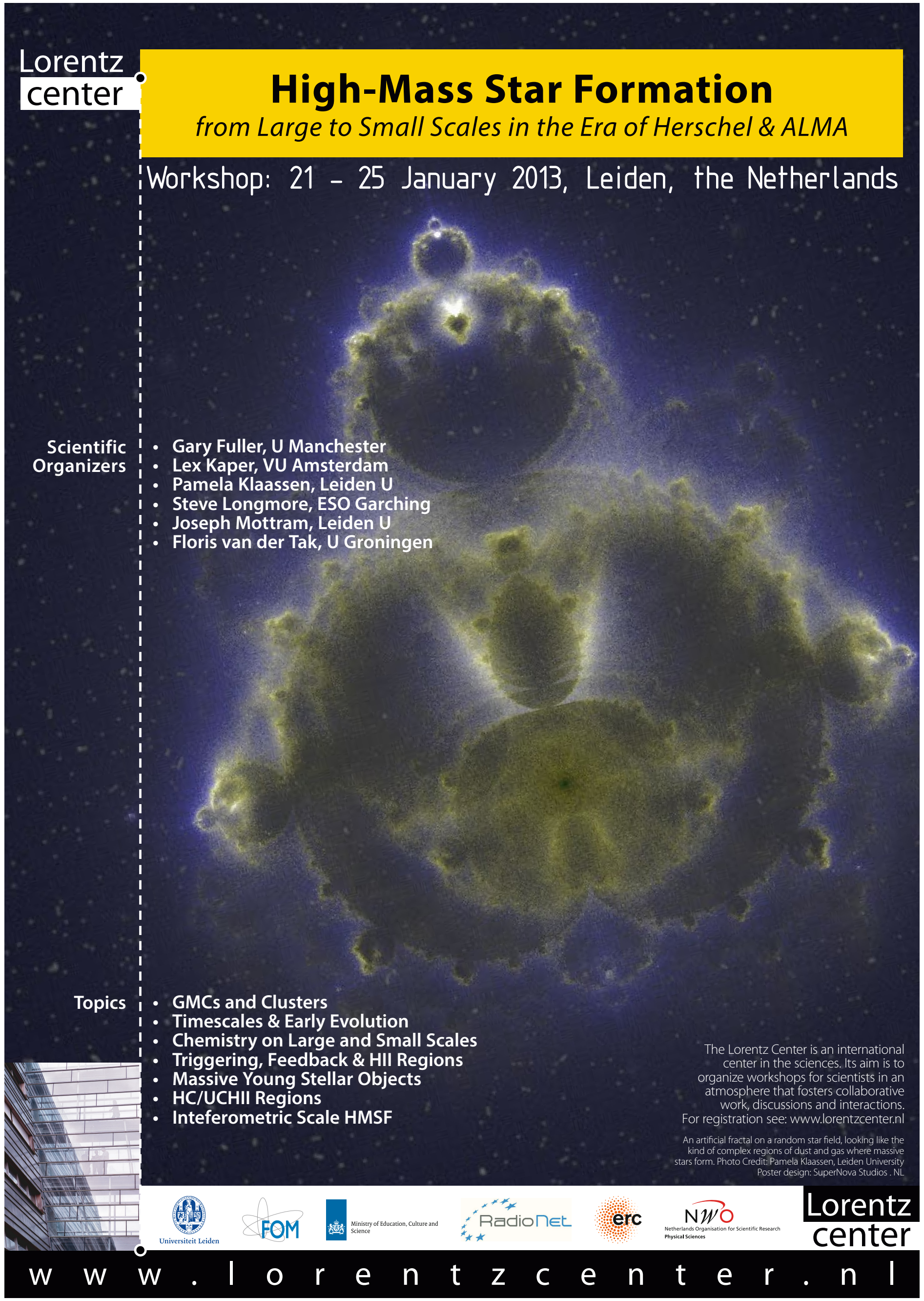
ALMA Early Science Massive Star Formation Workshop

held at ESO Headquarters, Garching Germany, 8 April 2011

Steven Longmore[1]
Leonardo Testi[1]
Pamela Klaassen[1]

[1] ESO

s



Lorentz center
High-Mass Star Formation
from Large to Small Scales in the Era of Herschel & ALMA
Workshop: 21 - 25 January 2013, Leiden, the Netherlands
Scientific Organizers
Gary Fuller, U Manchester
Lex Kaper, VU Amsterdam
Pamela Klaassen, Leiden U
Steve Longmore, ESO Garching
Joseph Mottram, Leiden U
Floris van der Tak, U Groningen
Topics
GMCs and Clusters
Timescales & Early Evolution
Chemistry on Large and Small Scales
Triggering, Feedback & HII Regions
Massive Young Stellar Objects
HC/UCHII Regions
Inteferometric Scale HMSF
The Lorentz Center is an international center in the sciences. Its aim is to organize workshops for scientists in an atmosphere that fosters collaborative work, discussions and interactions.
For registration see: www.lorentzcenter.nl
An artificial fractal on a random star field, looking like the kind of complex regions of dust and gas where massive stars form. Photo Credit: Pamela Klaassen, Leiden University
Poster design: SuperNova Studios . NL
Universiteit Leiden
FOM
Ministry of Education, Culture and Science
RadioNet
erc
NWO
Netherlands Organisation for Scientific Research
Physical Sciences
Lorentz center
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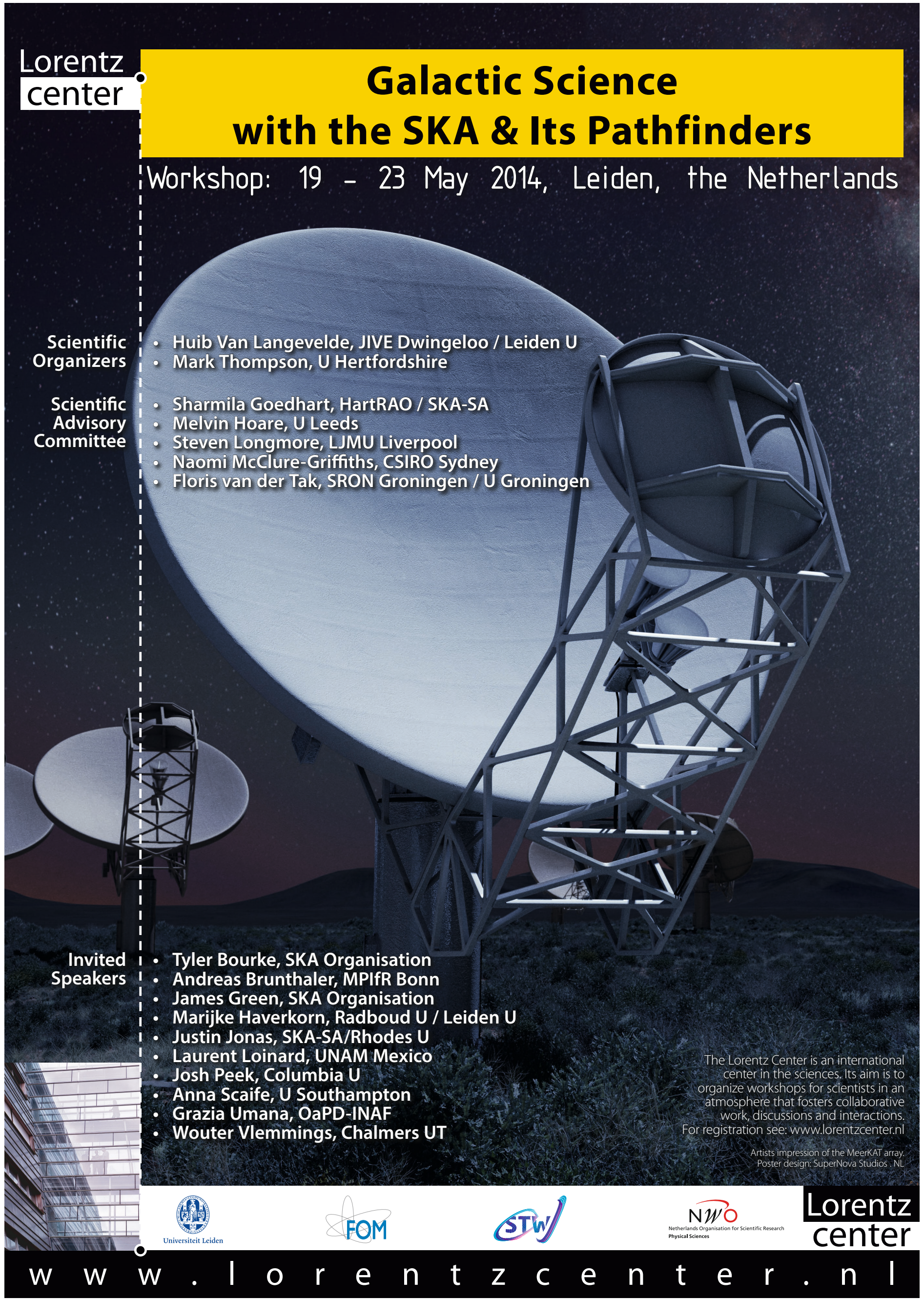

Lorentz center
Galactic Science with the SKA & Its Pathfinders
Workshop: 19 - 23 May 2014, Leiden, the Netherlands
Scientific Organizers
Huib Van Langevelde, JIVE Dwingeloo / Leiden U
Mark Thompson, U Hertfordshire
Scientific Advisory Committee
Sharmila Goedhart, HartRAO / SKA-SA
Melvin Hoare, U Leeds
Steven Longmore, LJMU Liverpool
Naomi McClure-Griffiths, CSIRO Sydney
Floris van der Tak, SRON Groningen / U Groningen
Invited Speakers
Tyler Bourke, SKA Organisation
Andreas Brunthaler, MPIfR Bonn
James Green, SKA Organisation
Marijke Haverkorn, Radboud U / Leiden U
Justin Jonas, SKA-SA/Rhodes U
Laurent Loinard, UNAM Mexico
Josh Peek, Columbia U
Anna Scaife, U Southampton
Grazia Umana, OaPD-INAF
Wouter Vlemmings, Chalmers UT
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For registration see: www.lorentzcenter.nl
Artists impression of the MeerKAT array.
Poster design: SuperNova Studios . NL
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NWO
Netherlands Organisation for Scientific Research
Physical Sciences
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Observational Priorities for 2020

Continued enhancement of ALMA

- Short/Medium term: Bandwidth increase + broadband receiver: improved continuum sensitivity and spectral line coverage
- Polarization: role of magnetic fields in suppressing fragmentation, accretion etc
- Medium/Long term: Focal plane arrays interesting technology to explore. Enhance mapping speed at high frequency. Major technical (and financial) challenge.

Access to a large, single dish (sub)mm telescope

- High-resolution, wide-field continuum/spectral line mapping
- Polarization: role of magnetic fields in suppressing fragmentation, accretion etc
- Find/understand environments of regions (to be) studied with ALMA
- Commensurate frequency coverage with ALMA desirable
- Continued (or enhanced) access to APEX is vital.

SKA Band 5

High spectral resolution near and mid-IR spectroscopy

High dynamic range, high angular resolution near to mid-IR imaging

Summary

Long-term goal: End-to-end description of star formation and feedback as a function of environment across cosmic time

Steps to reach the long term goal

1. Facilities: Broad initial consensus among HMSF community about (λ>sub-mm) science needs. How broad? Worth extending question to λ<sub-mm?

2. Observational community: A unified, concerted effort to observe statistically-meaningful samples of HMSF regions from stellar to GMC scales at all evolutionary stages and in all representative SF environments

3. Simulations community: Simulations representative of all SF environments with self-consistent initial conditions and full range of feedback

4. Observational + Simulation community: Develop tools necessary to directly compare observations and theory/simulations