Atacama
Large
Millimeter/submillimeter
Array

Star Formation in the ALMA Era

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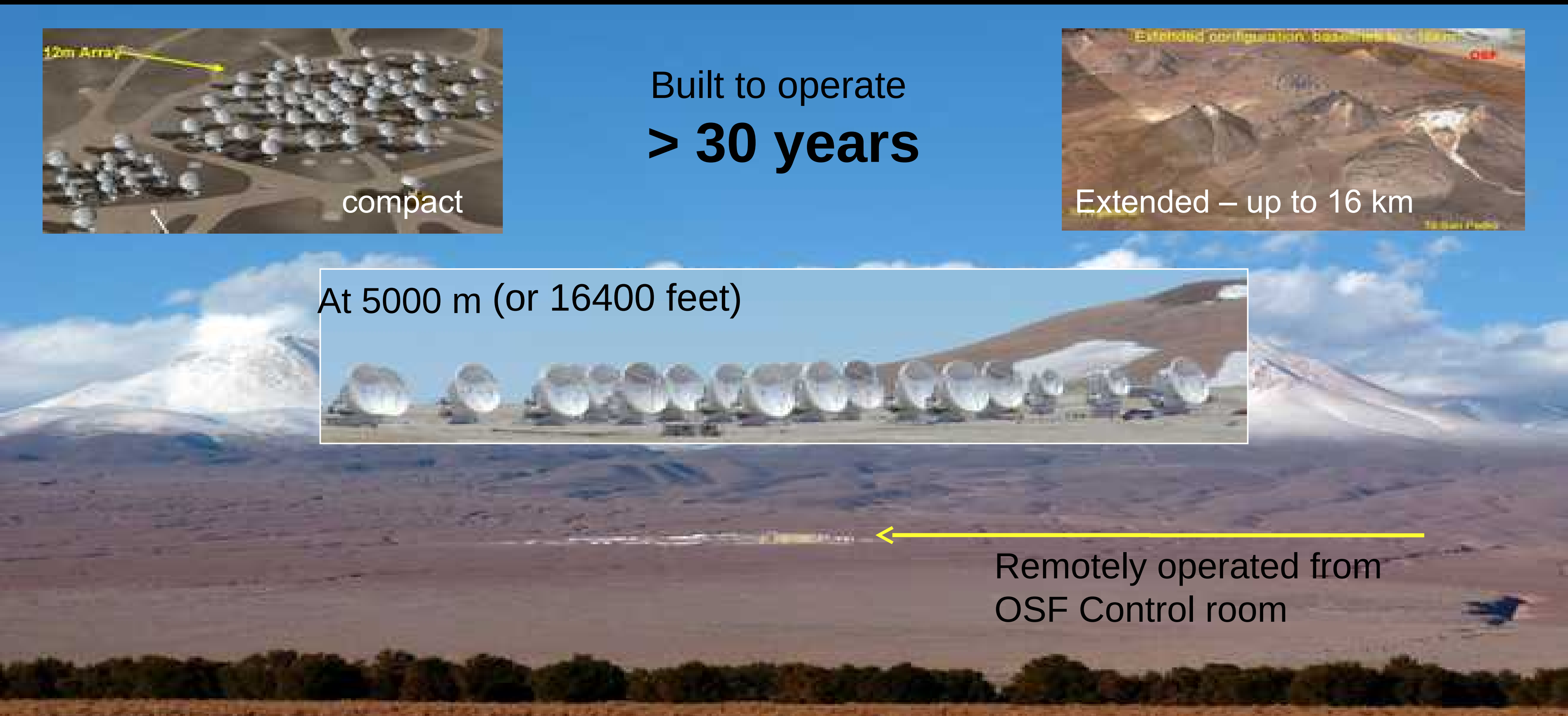
(ESO/ALMA)

Star Formation in Different Environments:
From Local Clouds to Distant Galaxies
Rencontres du Vietnam
August 6-12, 2017
Quy Nhon'n, Vietnam

Outline/Synopsis

- Highlight the recent advances in wide-field and high resolution surveys and detail numerical simulations of star formation in different environments, from individual stars to galaxy systems
- Search for a universal picture of star formation across all scales and identify the characteristics of each individual scale
- Goal is to share views from different research communities and encourage collaborations.

From the Abstract Book of this Conference



12m Array
compact
Built to operate
> 30 years
OSF
Extended – up to 16 km
At 5000 m (or 16400 feet)
Remotely operated from
OSF Control room

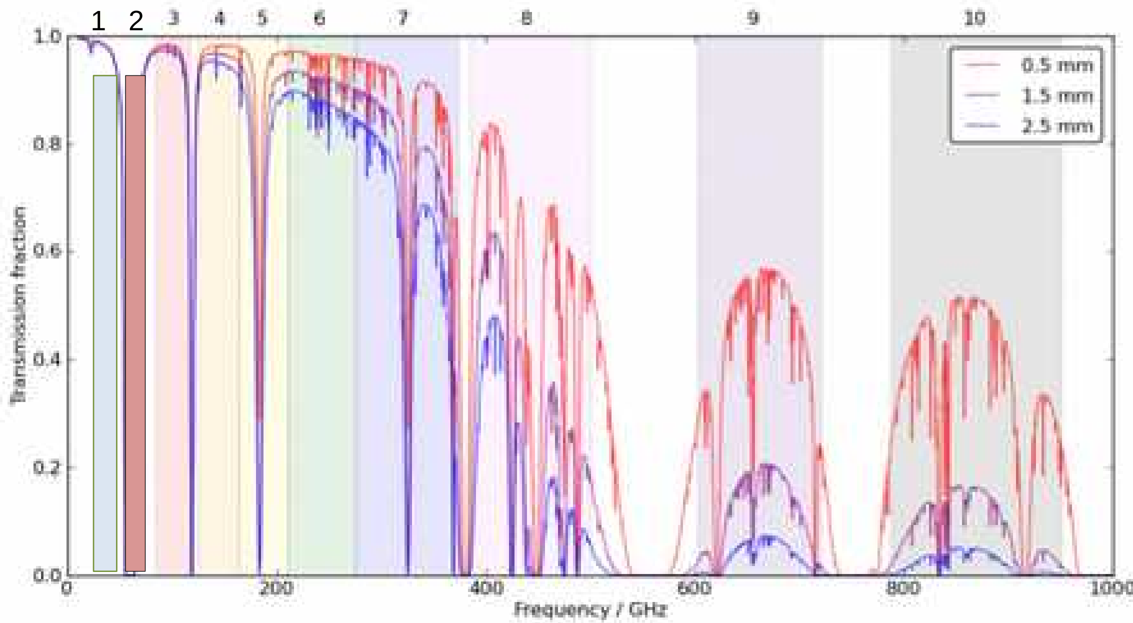
ALMA Status

- <u>All 66 antennas available</u>: currently all antennas are at the high site (AOS), of which 50+ on average are being used for science observations, including the ACA (Atacama Compact Array) or Morita Array - 12x7-m antennas and 4x12-m antennas for Total Power observations.
- After very successful Long Baseline Campaign in 2014, long baselines have been offered for PI science since in Cycle 3.
- From cycle to cycle, gradual increase of new capabilities (e.g., polarization, Solar, VLBI….).
- In Cycle 5: Band 5, polarization in Bands 4 & 5, increase of 33% observing time, 16 km baseline max.

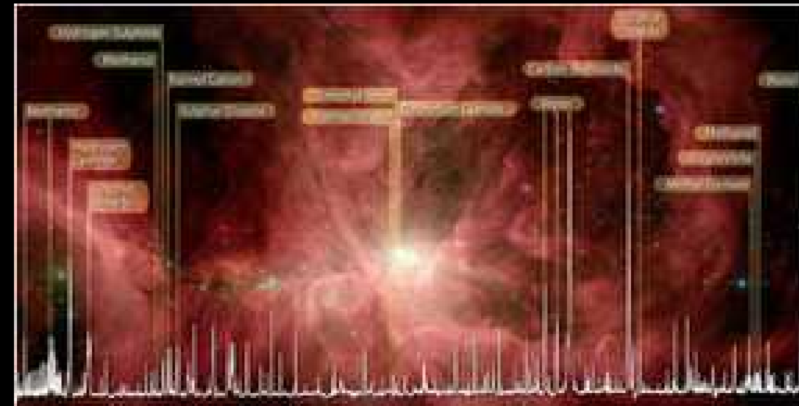
ALMA Status: Receivers

Receiver Bands currently installed, newly available on all antennas, in construction and under development:

- Band 1: 6 mm (35-52 GHz)
- Band 2: 4 mm (65-90 GHz)
- Band 3: 3 mm (84-116 GHz)
- Band 4: 2 mm (125-163 GHz)
- Band 5: 1.5 mm (163-211 GHz)
- Band 6: 1 mm (211-275 GHz)
- Band 7: 850 µm (275-370 GHz)
- Band 8: 650 µm (385-500 GHz)
- Band 9: 450 µm (602-720 GHz)
- Band 10: 350 µm (787-950 GHz)



" We've discovered a massive dust and gas cloud which is either the beginning of a new star or just a hell of a lot of dust and gas."



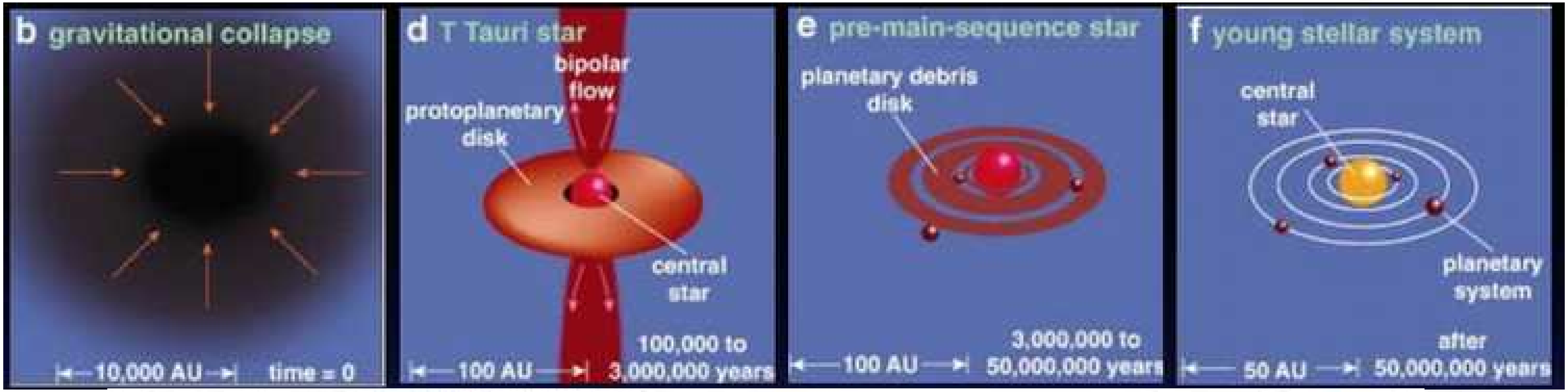
ALMA and Star Formation

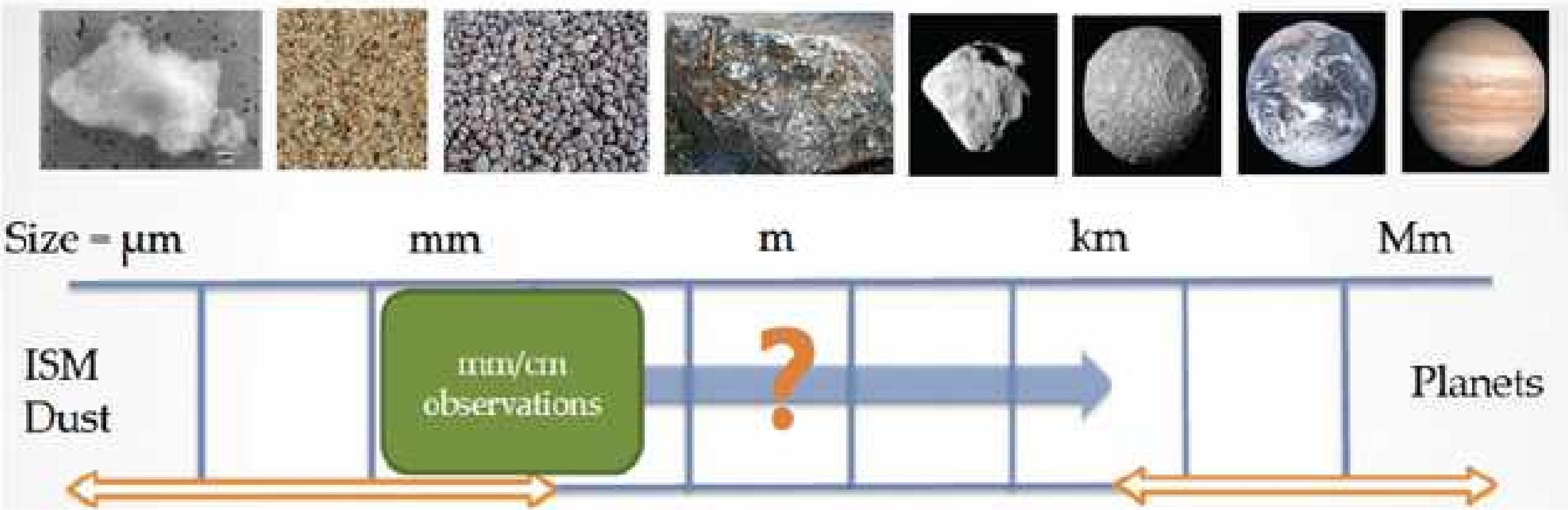
- Dust continuum, molecular/atomic line emission & polarization
- Explores the entire mm/submm available range from 84 to 950 GHz
- High sensitivity → unbiased surveys and probing deep near & far
- High spatial resolution → exploring the small-scale properties of star-forming regions, spatial coincidence of lines & species
- High spectral resolution → dynamics, limiting line confusion
- Large frequency coverage → physical properties, exploring molecular complexity
- Good calibration → consistent relative line intensities

Other mm/submm Interferometers in the ALMA Era

· Formation of Stars & Planets

Protostars → Planets

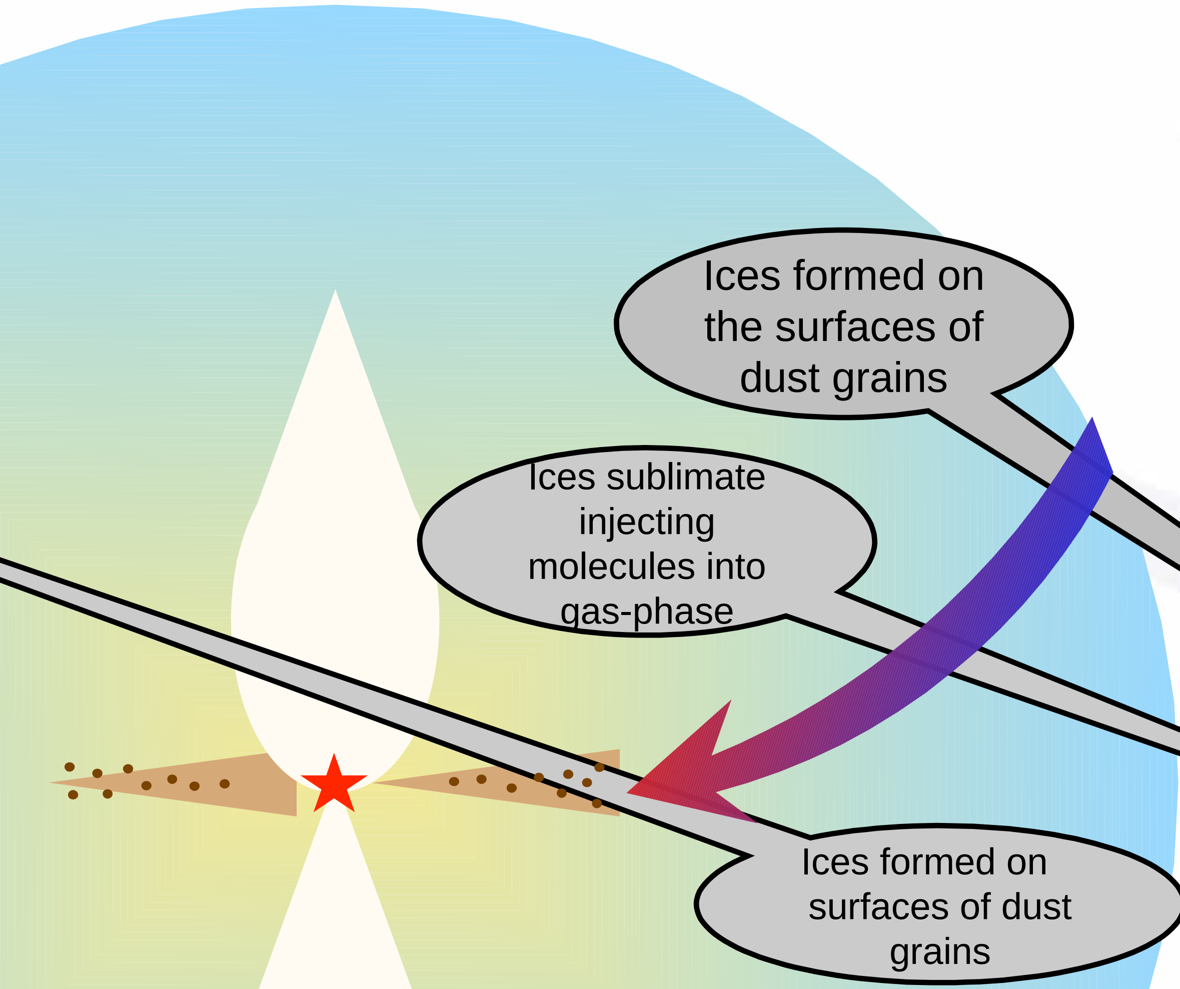




Follow evolution of gas and dust to the smallest scales

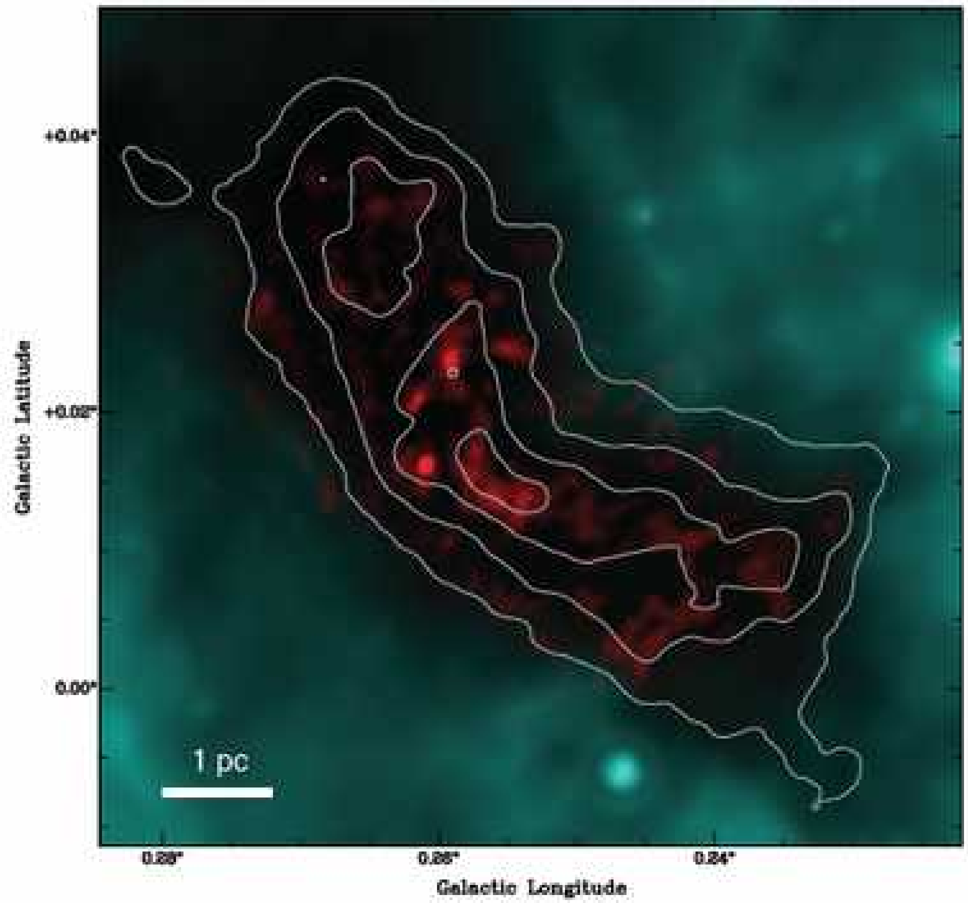
Following the Evolution of Gas and Dust to the Smallest Scales

- What molecules are formed as material is accreted to the circumstellar disk – and how?
- How is the rich chemistry of the earliest protostellar stages incorporated into emerging planetary systems?



Courtesy: J. Jorgensen

A Cluster in the Making: G0.253+0.016



24 μm from Spitzer; ALMA in red; contours SCUBA 450 μm

- G0.253+0.016 is a molecular clump that appears to on the verge of forming a high-mass cluster
- ALMA 3mm and molecular emission at small scale (~0.07 pc) revealing a network of complex filamentary structures
- Statistical analysis supports the idea that turbulence shapes the observed structure
- The cloud is on the verge of forming a cluster from hierarchical, filamentary structures that arise from a highly turbulent medium

Rathborne et al. 2015 ApJ 802, 125

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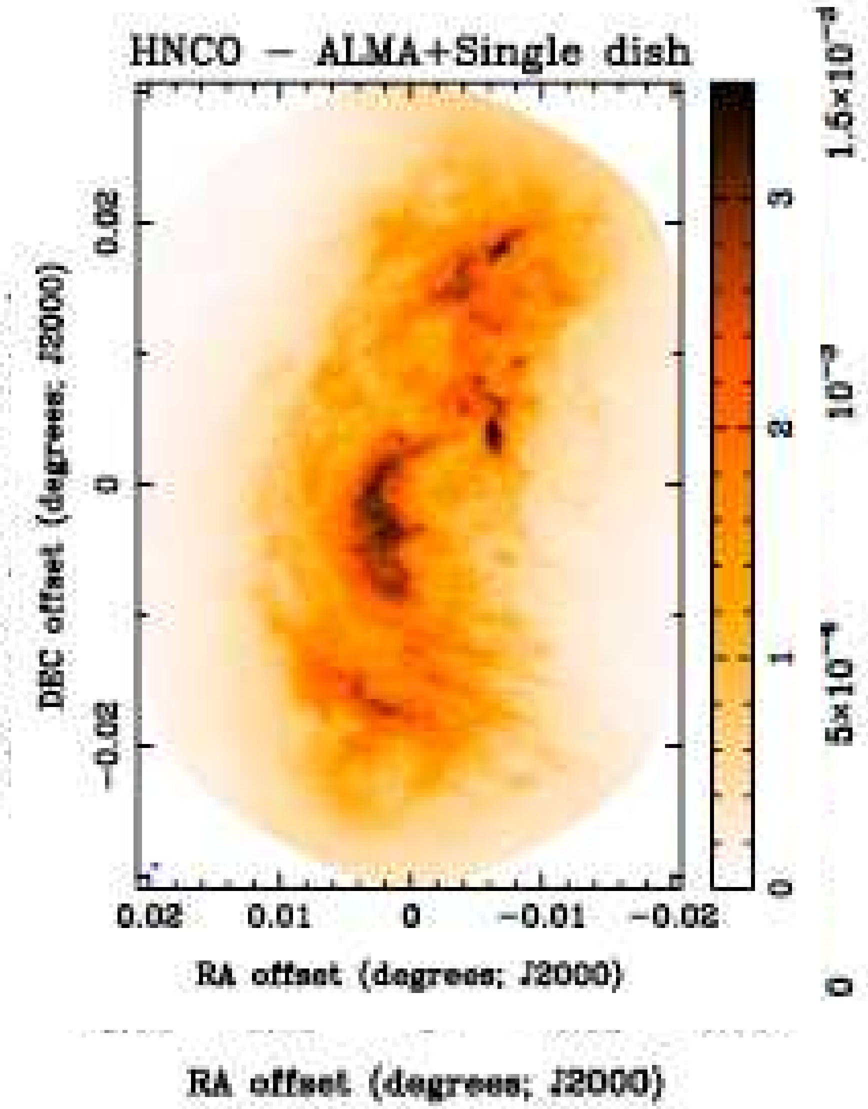

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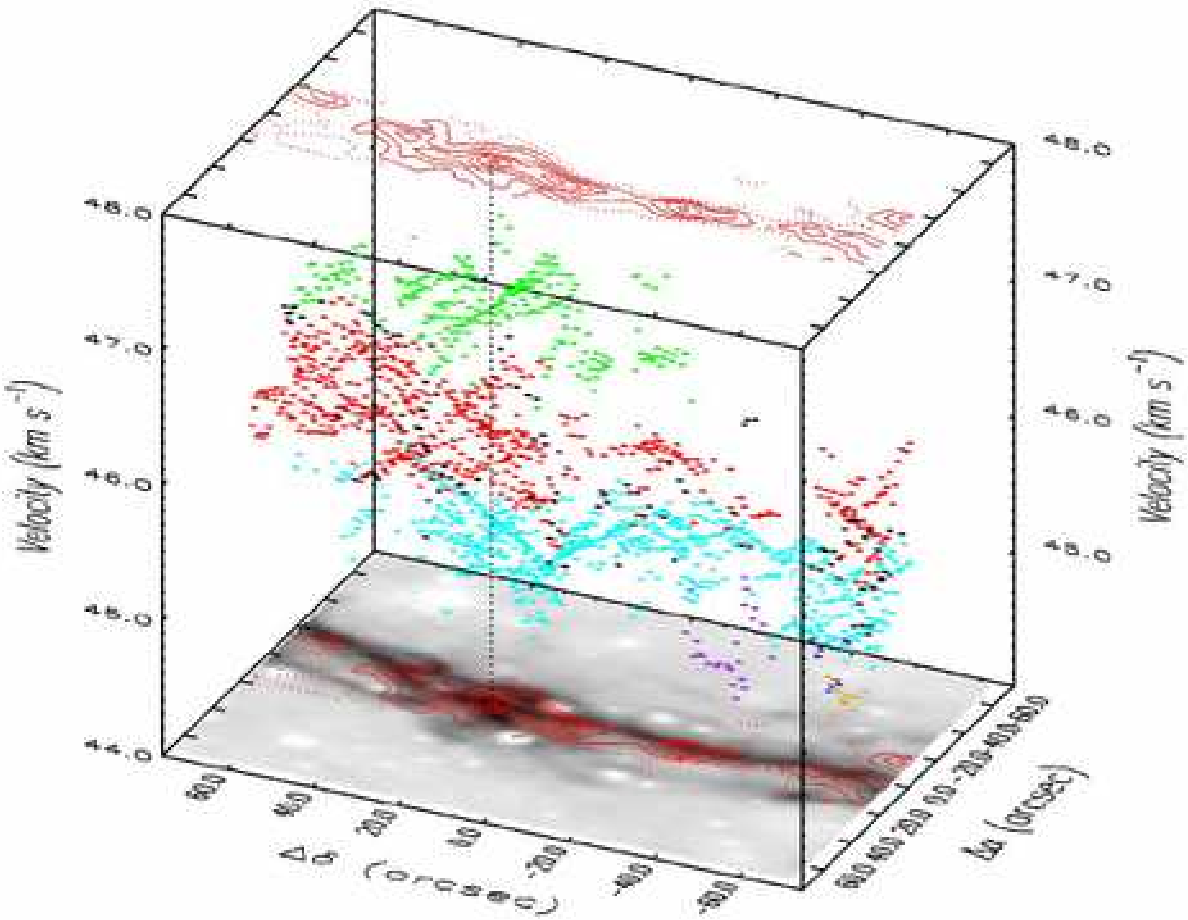
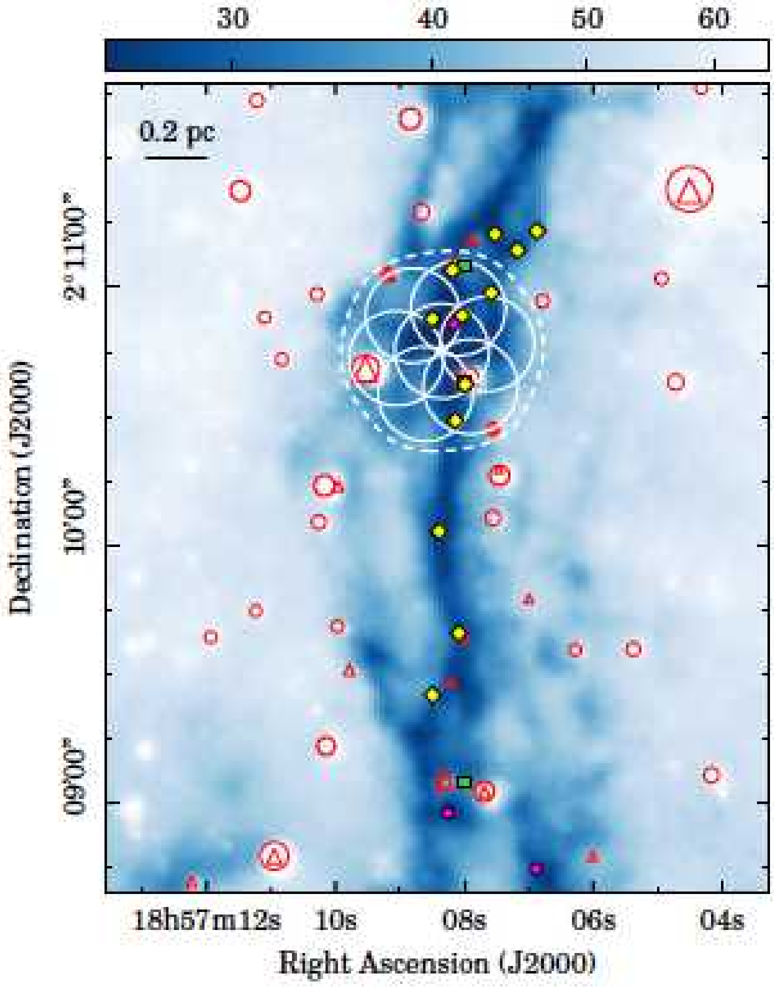
Filament Structure in the Dark Cloud G35.28

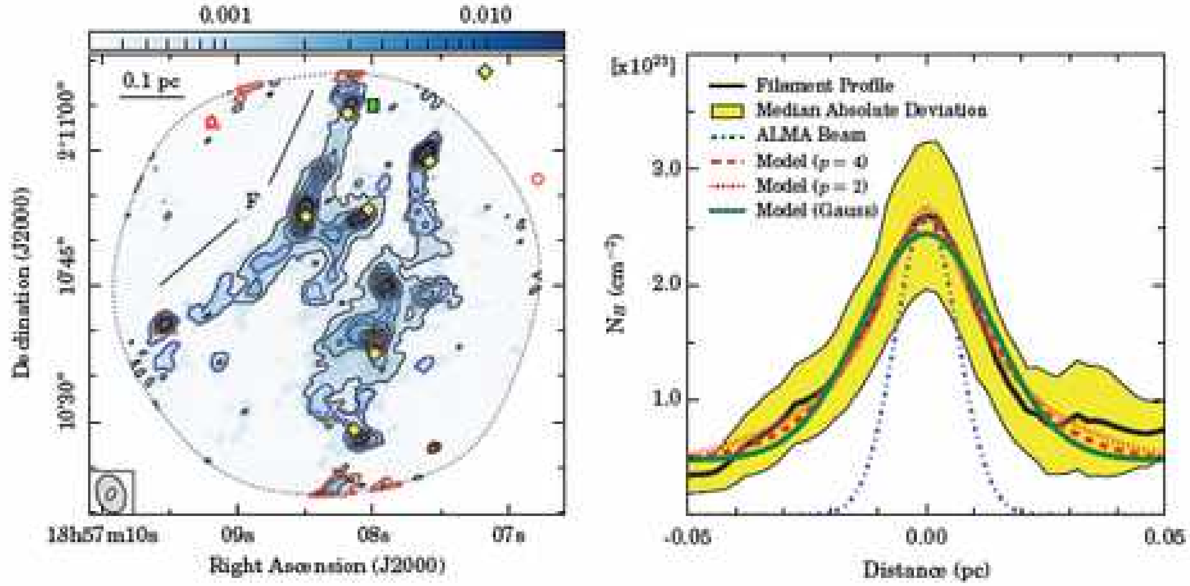


- PdBI observations
- Analysis of $N_2H^+(1\text{-}0)$ reveal three sub-filaments with Δv ~ 1 to 1.5 km s^{-1}
- Highly complex environment with several mildly supersonic filaments
- Dynamical processes on local scales with systematic trends observed towards several continuum peaks
- Sea-saw velocity pattern consistent with flow along filaments

Henshaw et al. 2016 MNRAS 463, 146

Zooming in into the Filament Structure in the Dark Cloud G35.28

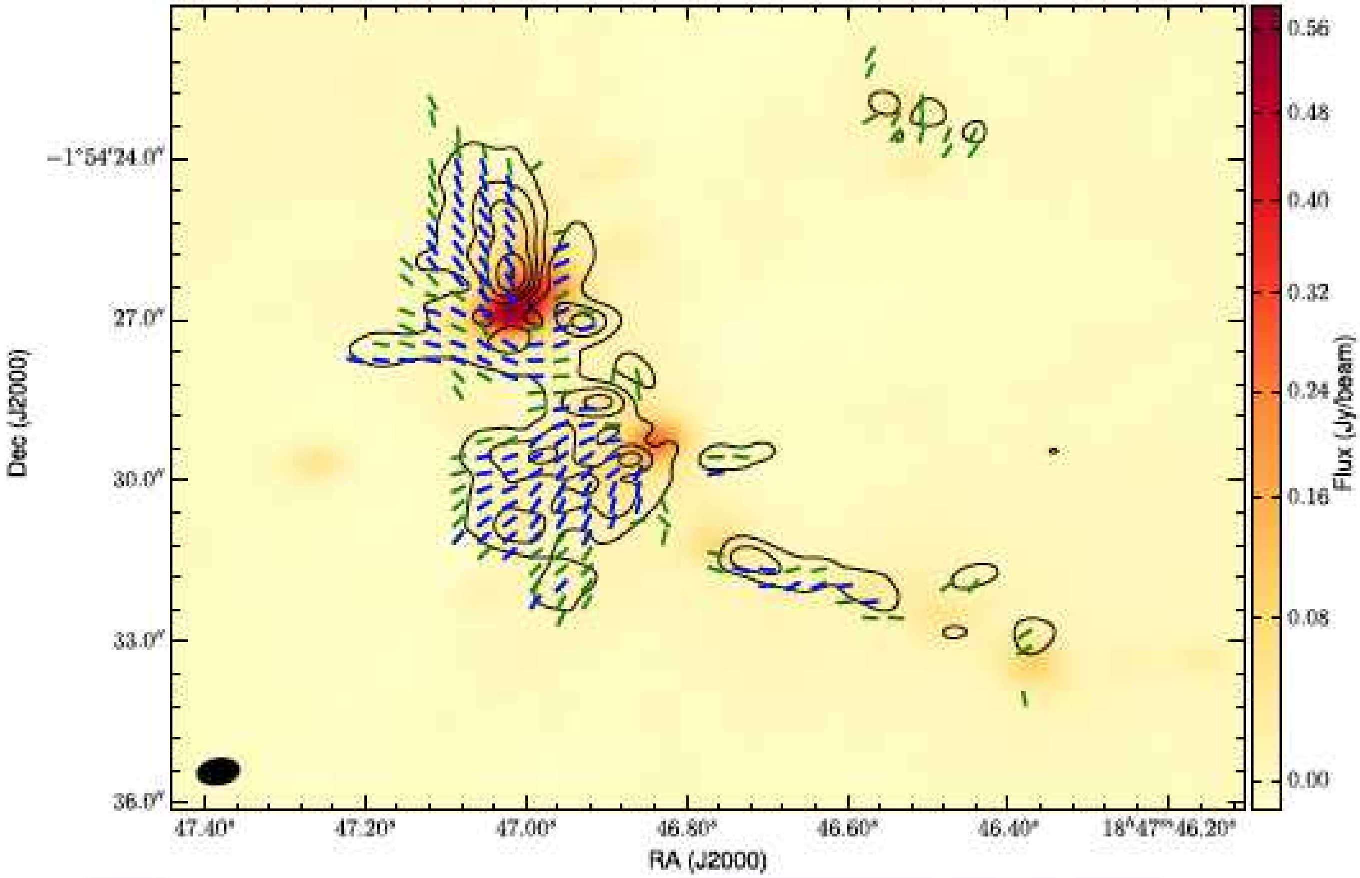




* ALMA observations of a 'proto-cluster hub'
* Dust continuum at 1.07 mm (0.02x0.01 pc) and high sensitivity (0.2 mJy beam -1 or 0.2 M⊙)
* Complex network of narrow (~0.03 pc) filamentary structures, a factor of 3 narrower than the 'proposed' width of filaments.
* 28 compact objects with 0.3<Mc/M⊙<10.4
* Coeval formation of low and high-mass stars

Henshaw et al. 2017 MNRAS 464, L13

The ALMA View of the B-Field in W43-MM1



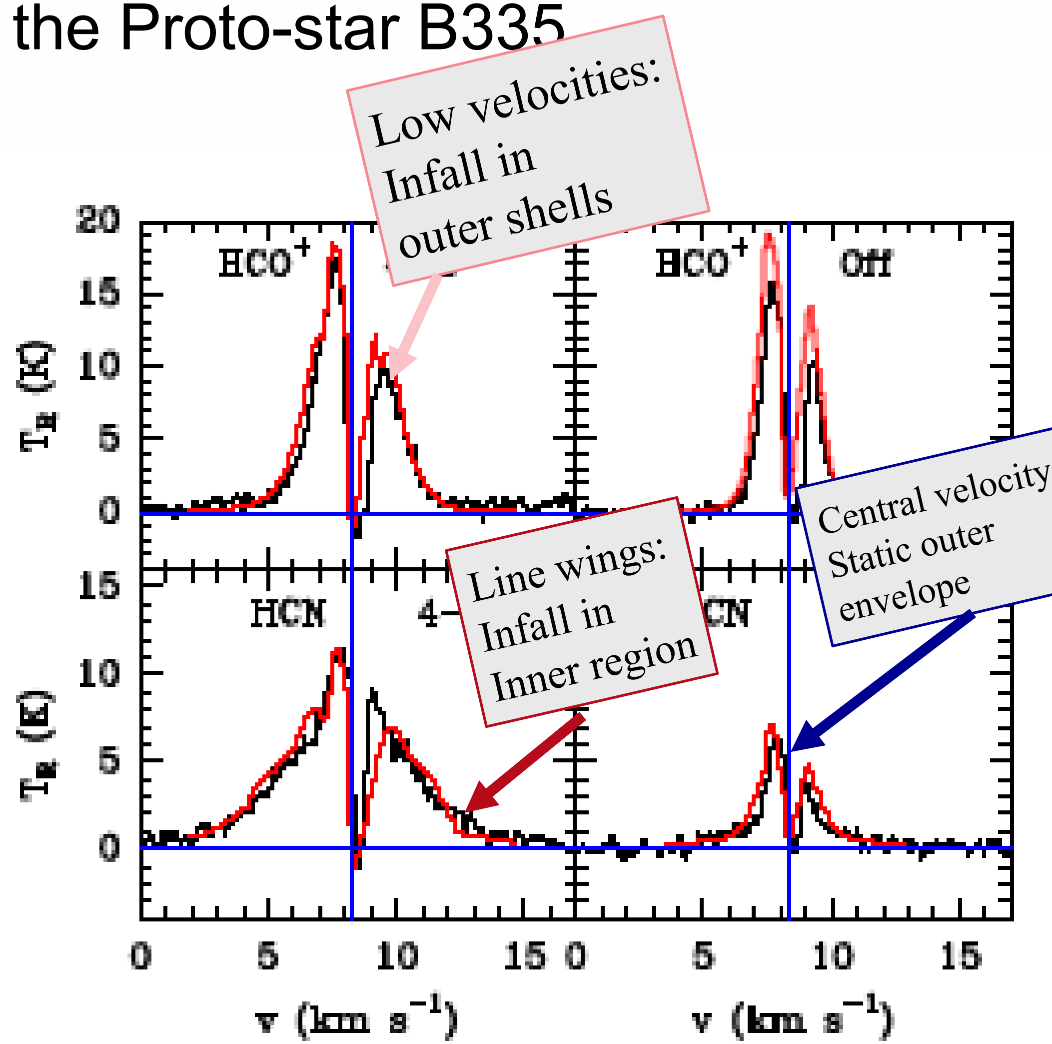
- High-mass star-forming clump W43-MM1
- ALMA first polarization measurements of 1mm dust emission
- Highly fragmented filaments (15) with source masses ranging from 14 to 312 M⊙

Cortes et al. 2016 ApJ 825, L15

Caught in the Act: Infall in the Proto-star B335

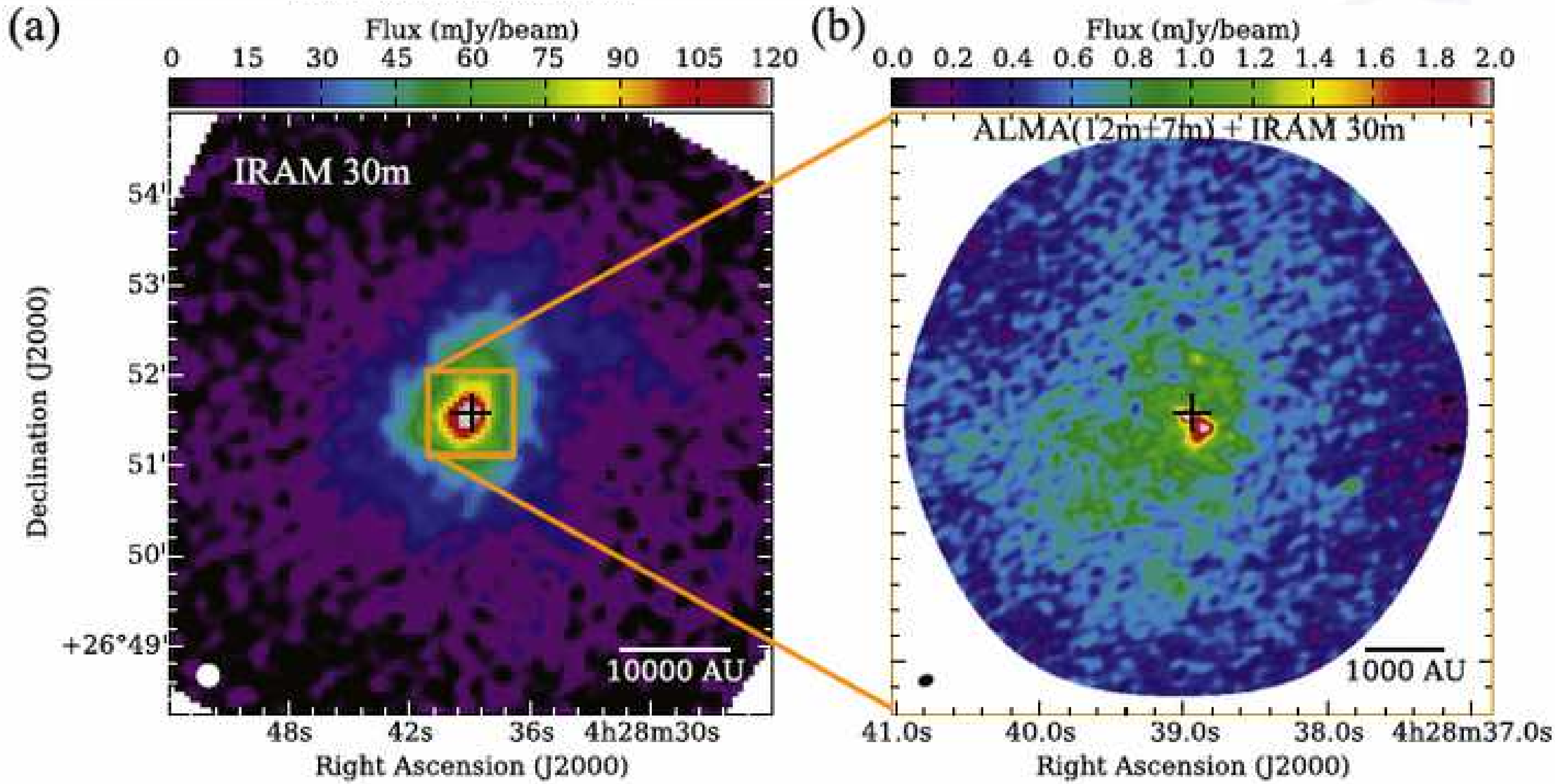
- Isolated globule B335 at 100pc
- Absorption features against the continuum that are red-shifted from the systemic velocity.
- Unambiguous evidence for infall towards the central luminous source.

- Infall radius is 0.012 pc
- Mass infall rate 3 x 10-6 M⊙yr-1
- Age is 5x104 yr and accumulated mass is 0.15 M⊙



Evans et al. 2015 ApJ 814, 22

Fragmentation and Collapse of a Dense Core MC27/L1521F



Tokuda et al. 2016 ApJ 826, 26

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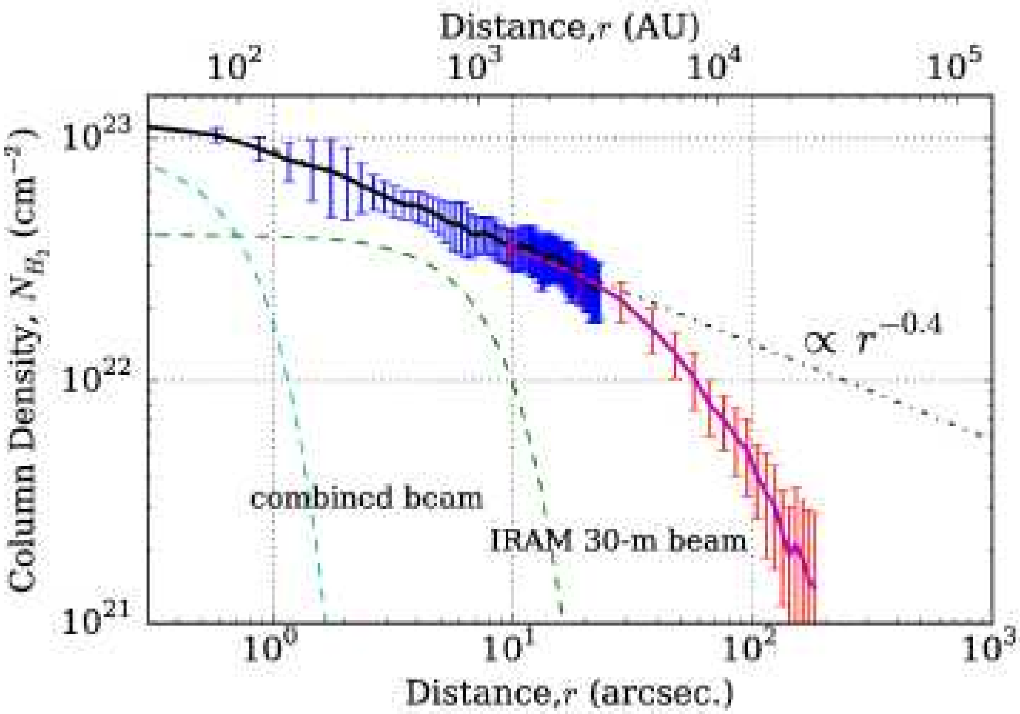
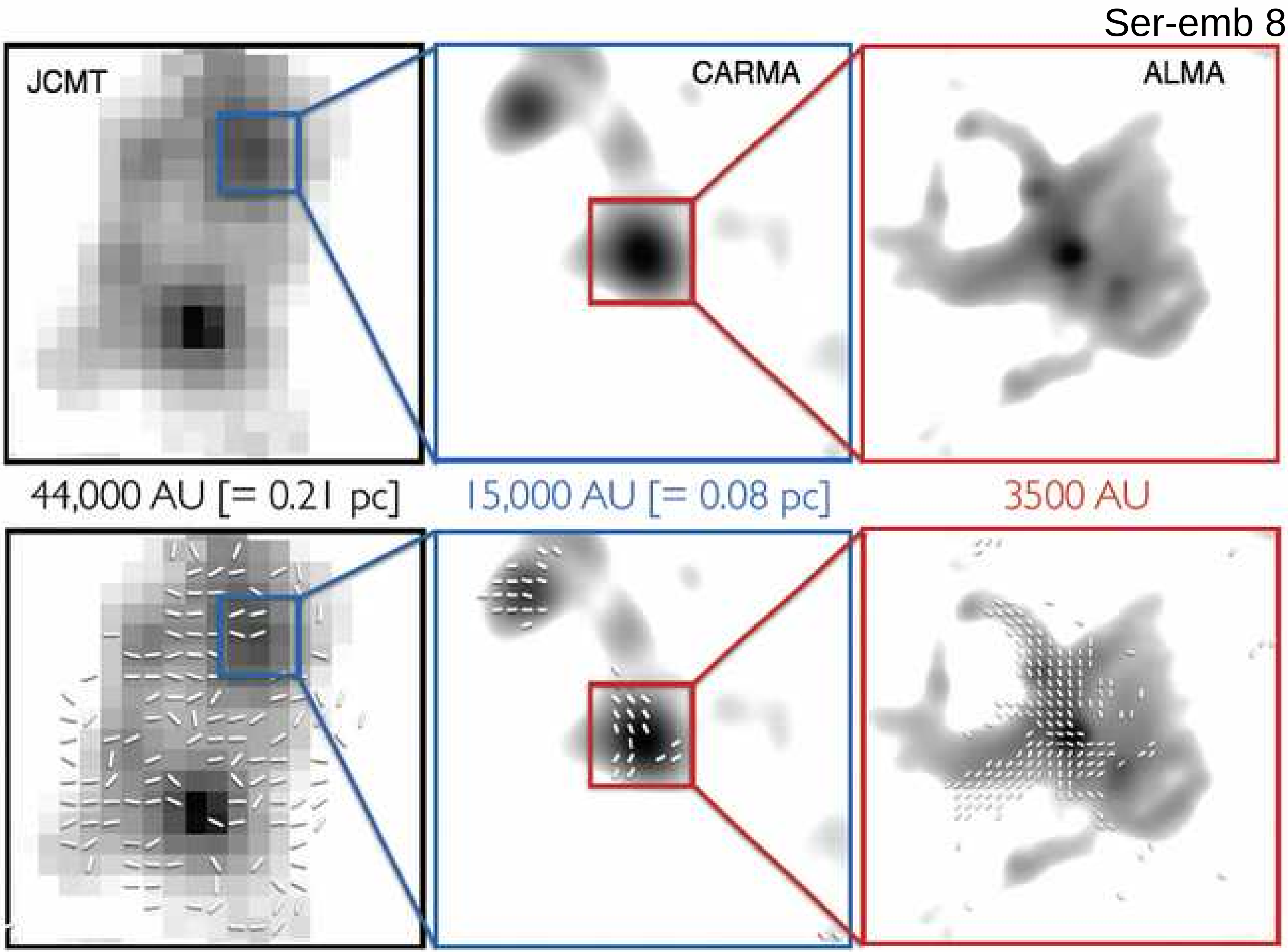


- The average radial column density distribution is $N_{H2} \sim r^{-0.4}$ in the inner part and $\sim r^{-1.0}$ in the outer part
- The inner flatter region harbors complex velocity/spatial structure, which may reflect the dynamical status of the dense core

Tokuda et al. 2016 ApJ 826, 26

Role of B-Field at the Smallest Scales of Star Formation



Hull et al. 2017 ApJ 824, L9

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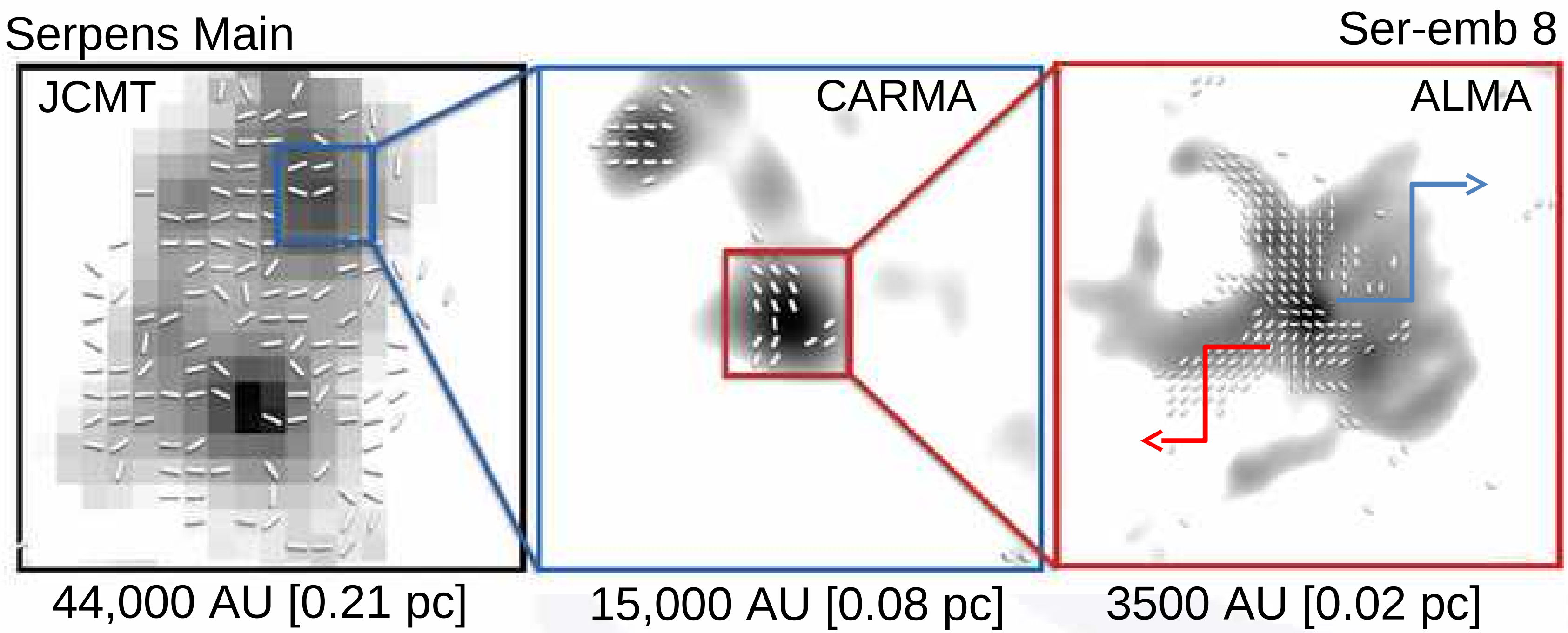


* The ALMA small-scale (~100 AU) B-Field, which is attached to the forming stellar system in Ser-emb 8, is not reminiscent of the large-scale field

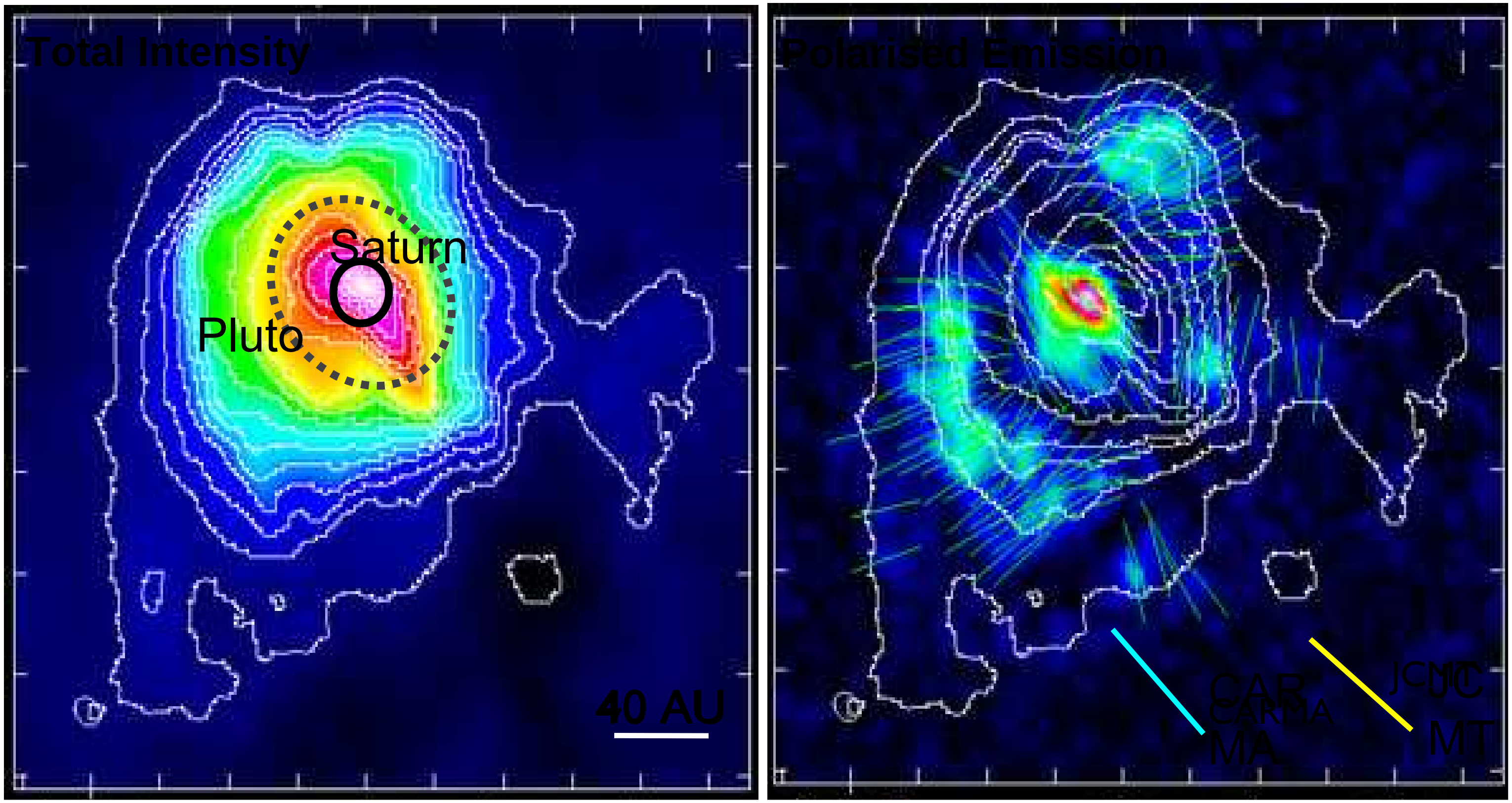
* No hourglass shape is seen!

* This is in contrast to theoretical views (e.g., Li et al. 2009) that suggest that the large-scale mean field direction could be preserved all the way down to the scale of forming stars.

* Suggesting alternate mode of star formation where the field morphology

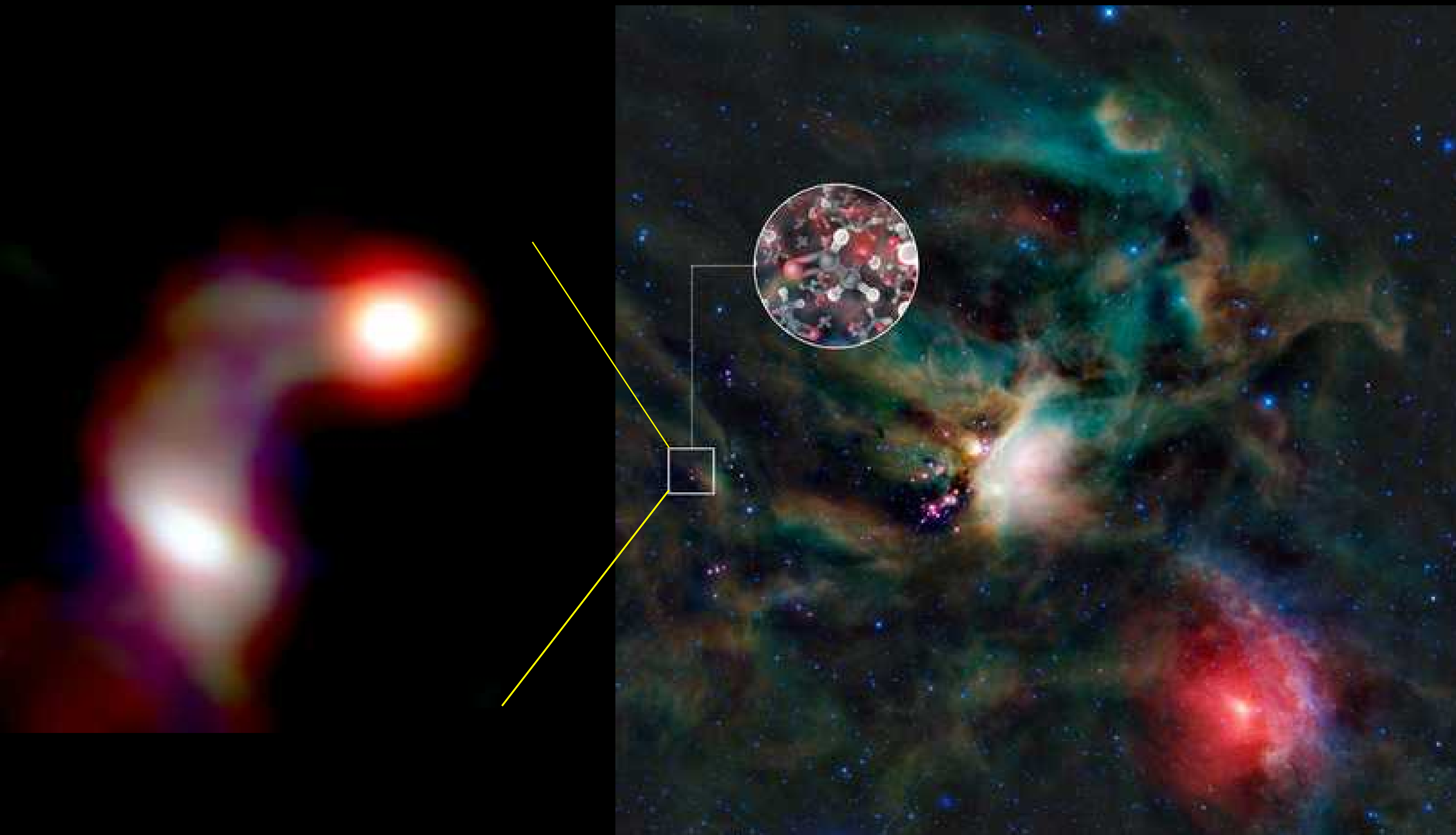
Hull et al. 2017 ApJ 824, L9

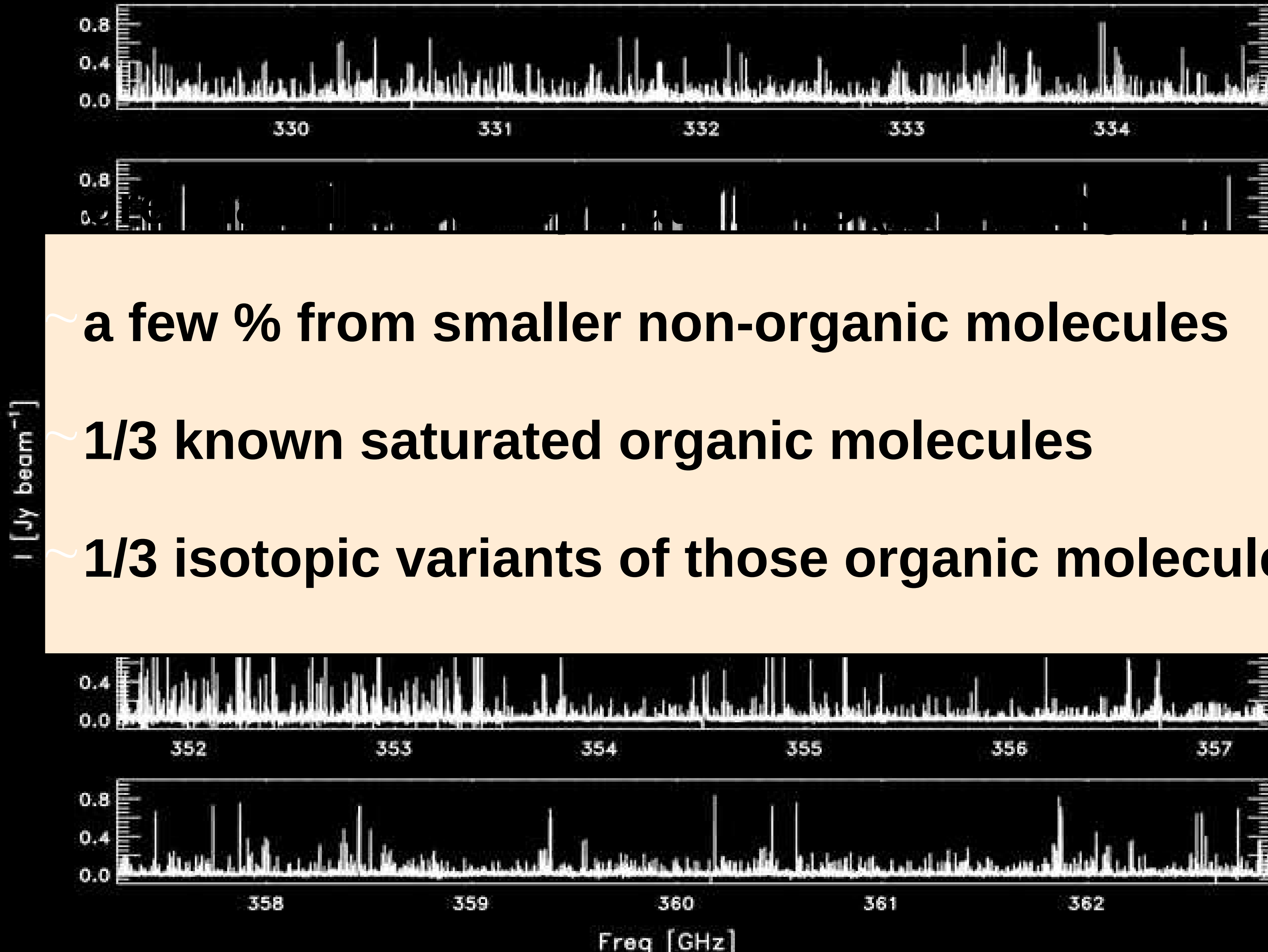
- Magnetic Field in a Protostar at Scales < 100 AU



- OMC3 is a young (t~104 yr), intermediate mass protostar (Mcore=36 M☉ ; Lbol<60 L☉)
- 14 km baseline in Band 6; tos~40min, 0.03”x0.02”, PA~40 deg (10 AU); rms (1σ) =33 μJy/beam
- Polarized emission peaks around center, although does not coincide with continuum peak; gaps between center and extended emission

S. Takahashi et al. (2017)



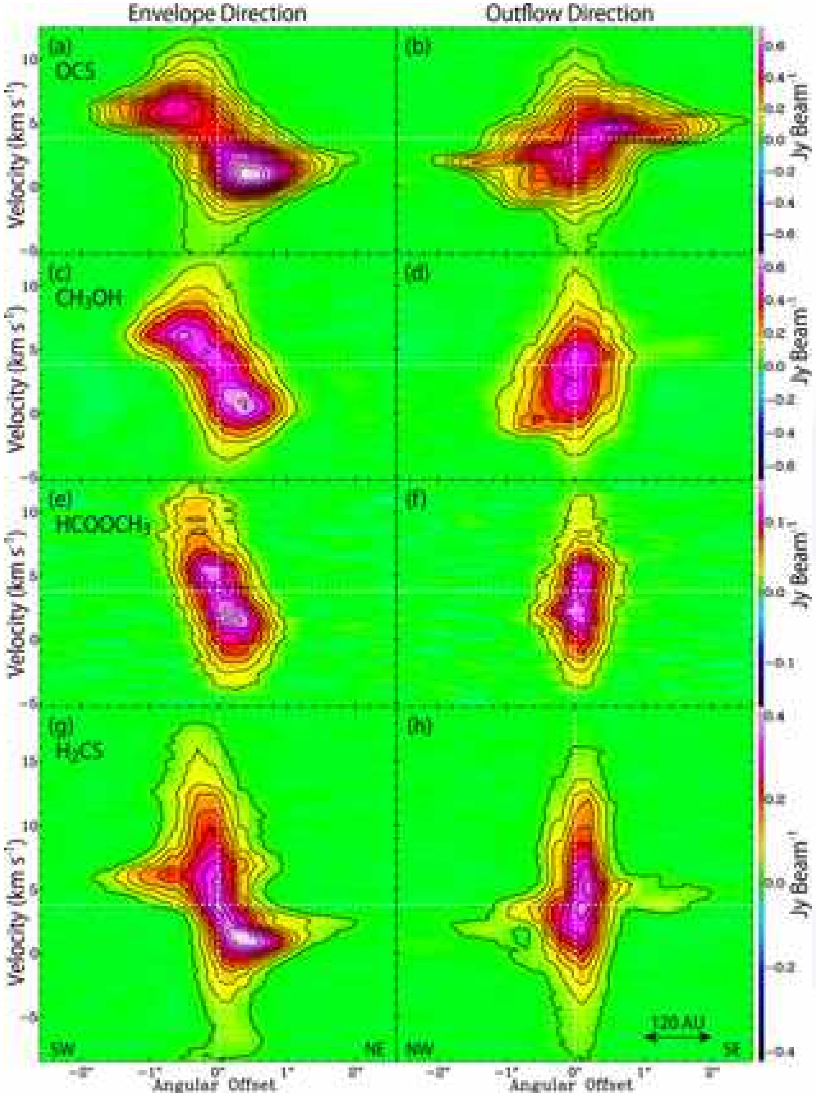


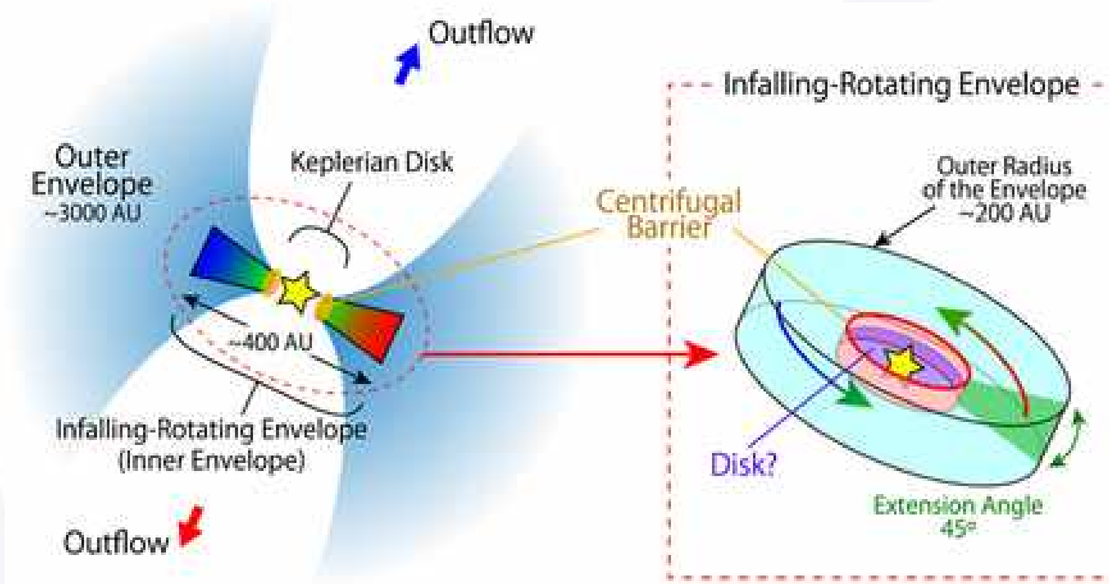
~a few % from smaller non-organic molecules

~1/3 known saturated organic molecules

~1/3 isotopic variants of those organic molecule

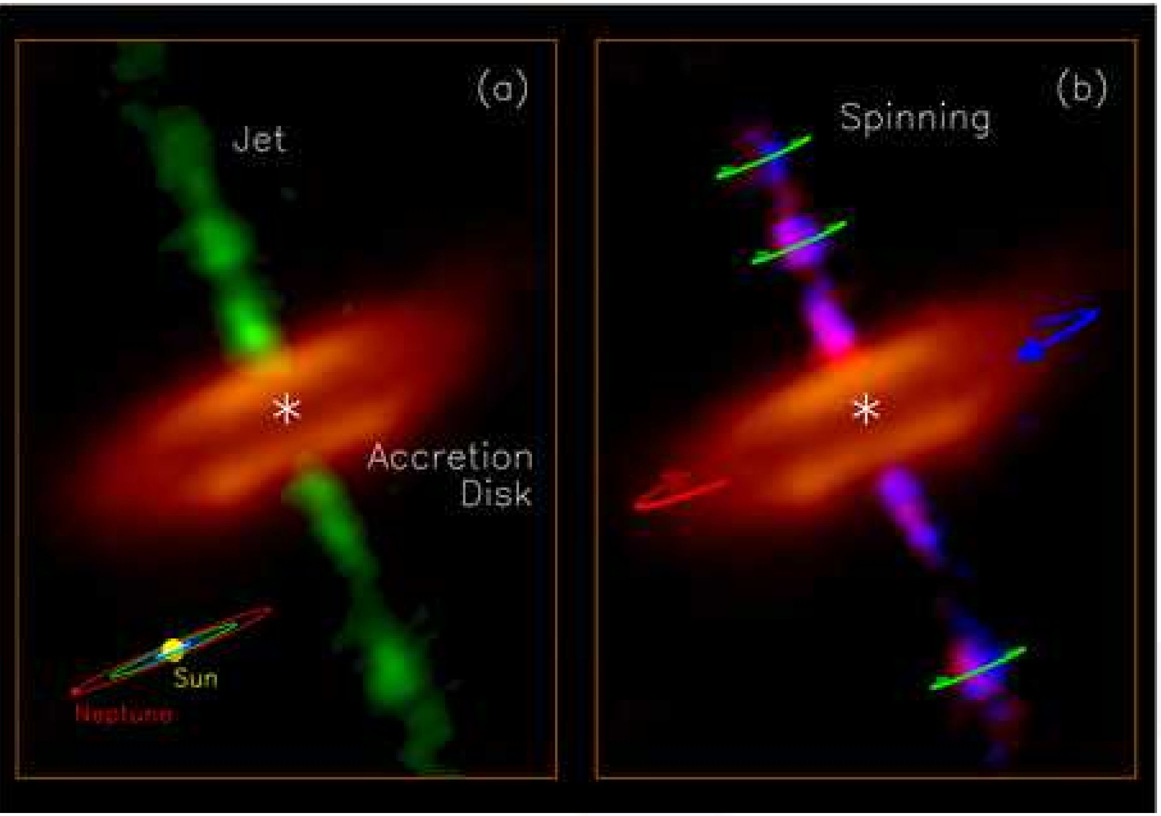
Infalling-Rotating Motion in IRAS 16293-2422 (Source A)





- Significant chemical differentiation at 50 AU scales
- OCS traces the infalling-rotating envelope
- CH3OH and HCOOCH3 are found in the inner part of the envelope
- The radius of the centrifugal barrier and the protostellar mass are evaluated to be

The Molecular Jet from the Innermost Disk of HH212

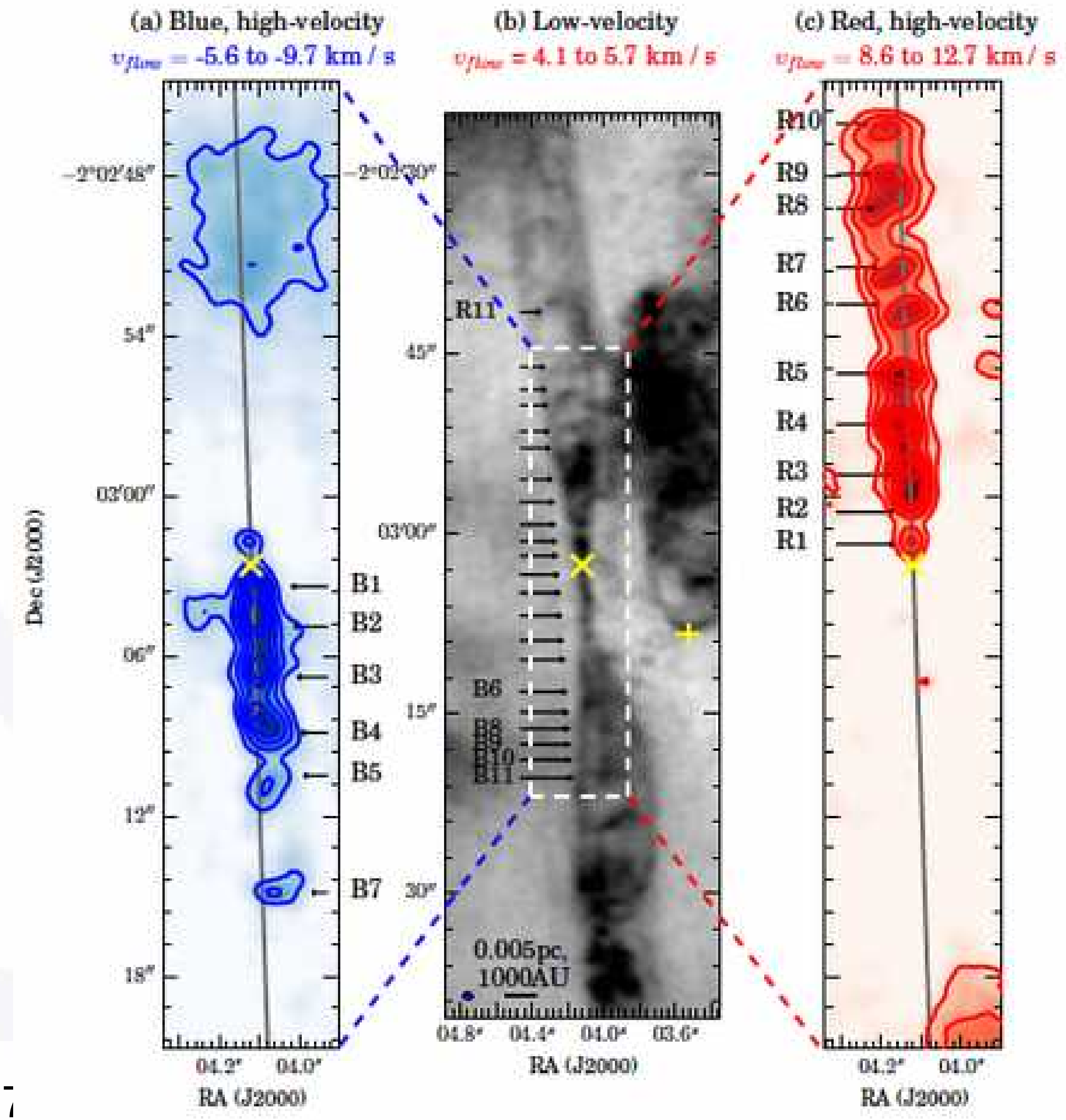


- A central problem in forming stars is the angular momentum in the disk which prevents material from falling into the central stellar core.
- Molecular outflows remove angular momentum at a range of disk radii
- The ALMA high-angular resolution data on HH212 - SiO(8-7) at 0.06” - allow to measure the rotation of the jet down to 10 AU from the protostar.
- Highly collimated jets remove the residual angular momentum at the 0.05 AU scale (jet launching radius), enabling the material in

Lee et al. a & b 2017 Nature

The Episodic Molecular Outflow in the Cluster Serpens South

- Episodic outflow observed in very young cluster
- Class 0 outflow showing episodic events
- The CO(2-1) emission reveals 22 distinct outflow ejecta features, with the most recent having the highest velocities
- The bipolar outflow originates from the peak of the 1 mm continuum emission – kinematics are consistent with rotation and infall
- Momentum and energy transfer to the environment



Plunkett et al. 2015 Nature 527, 7

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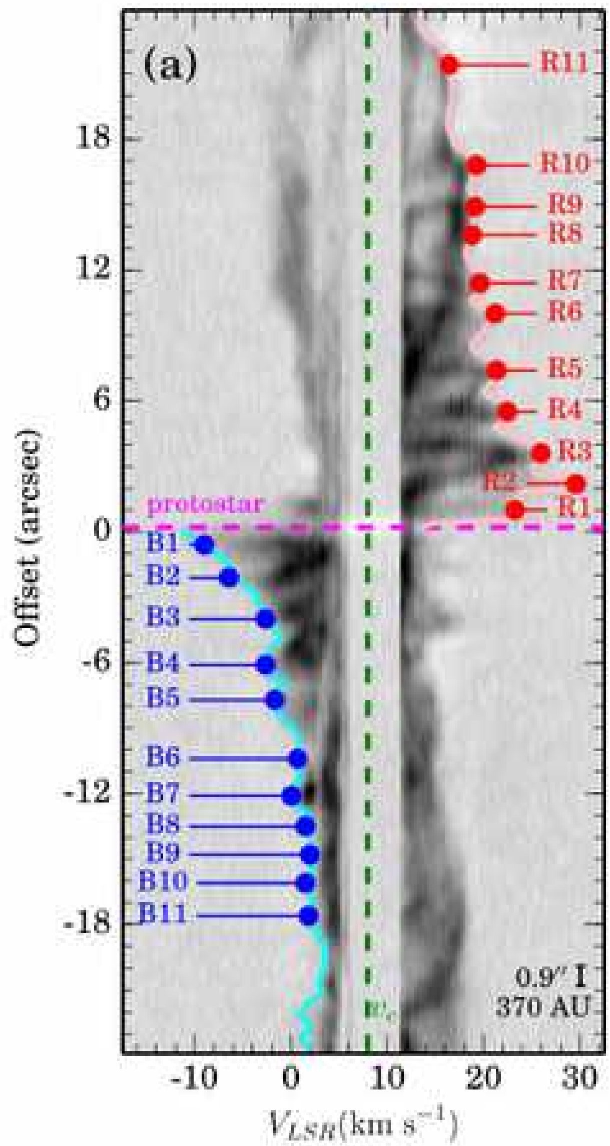
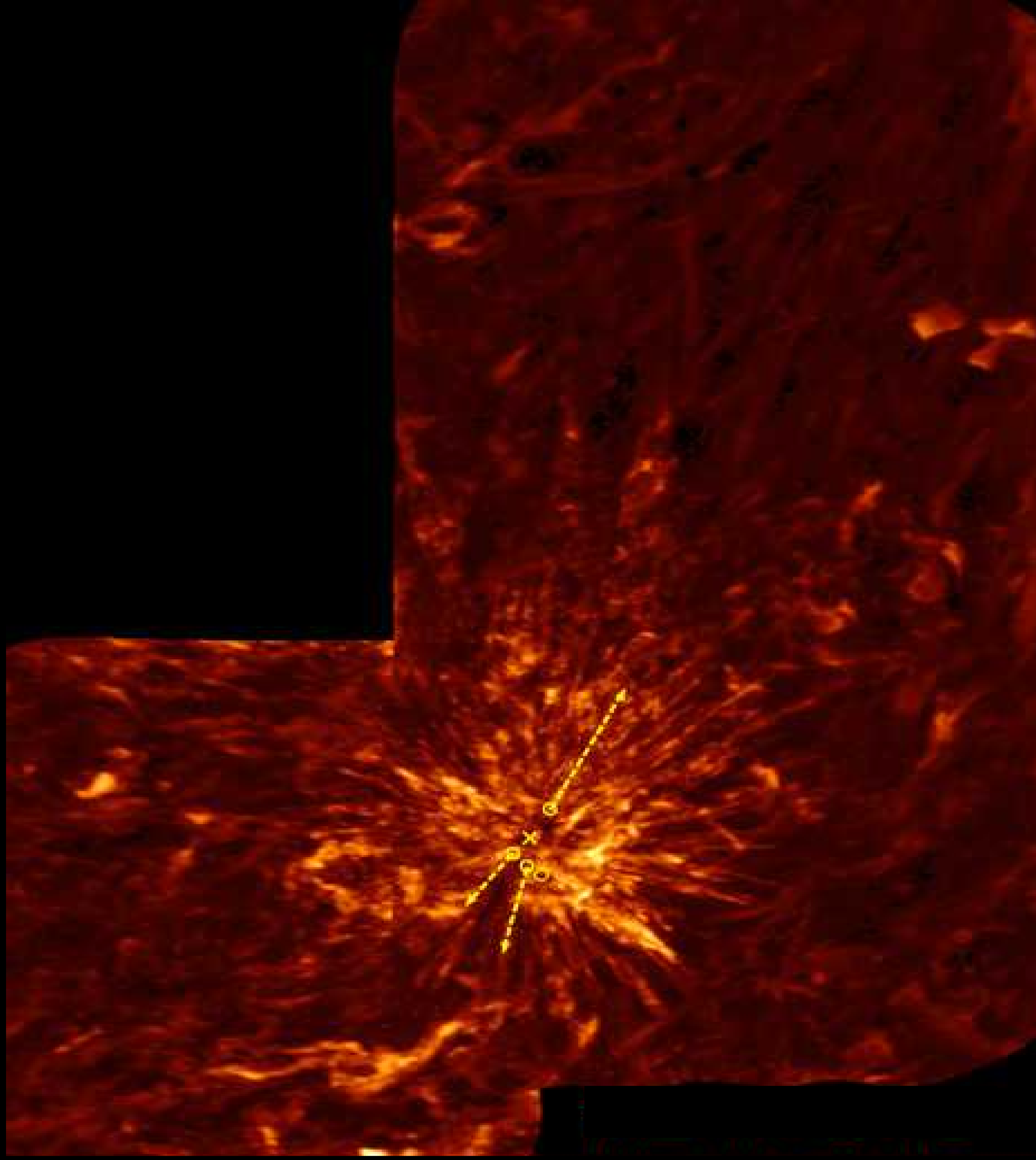
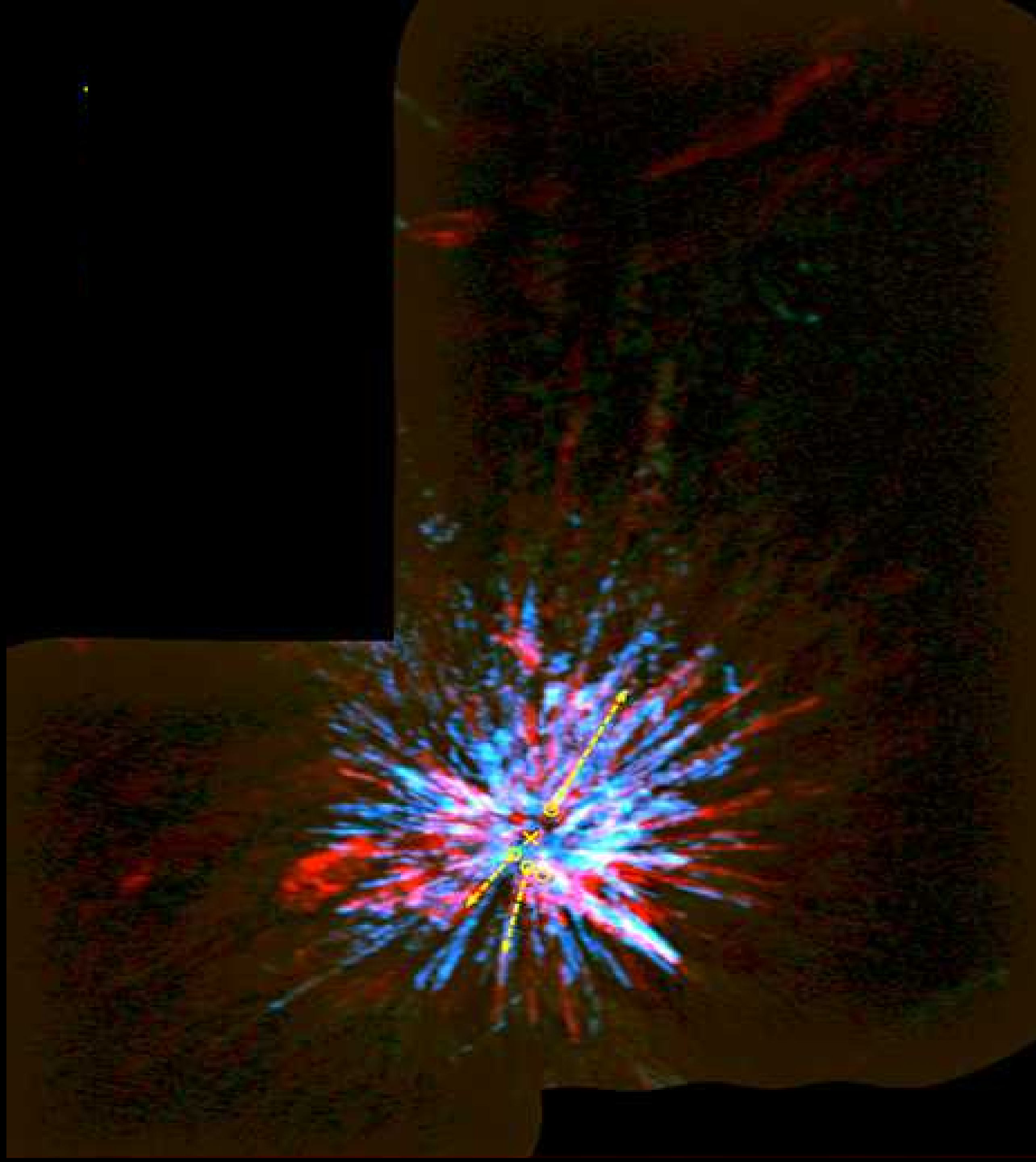
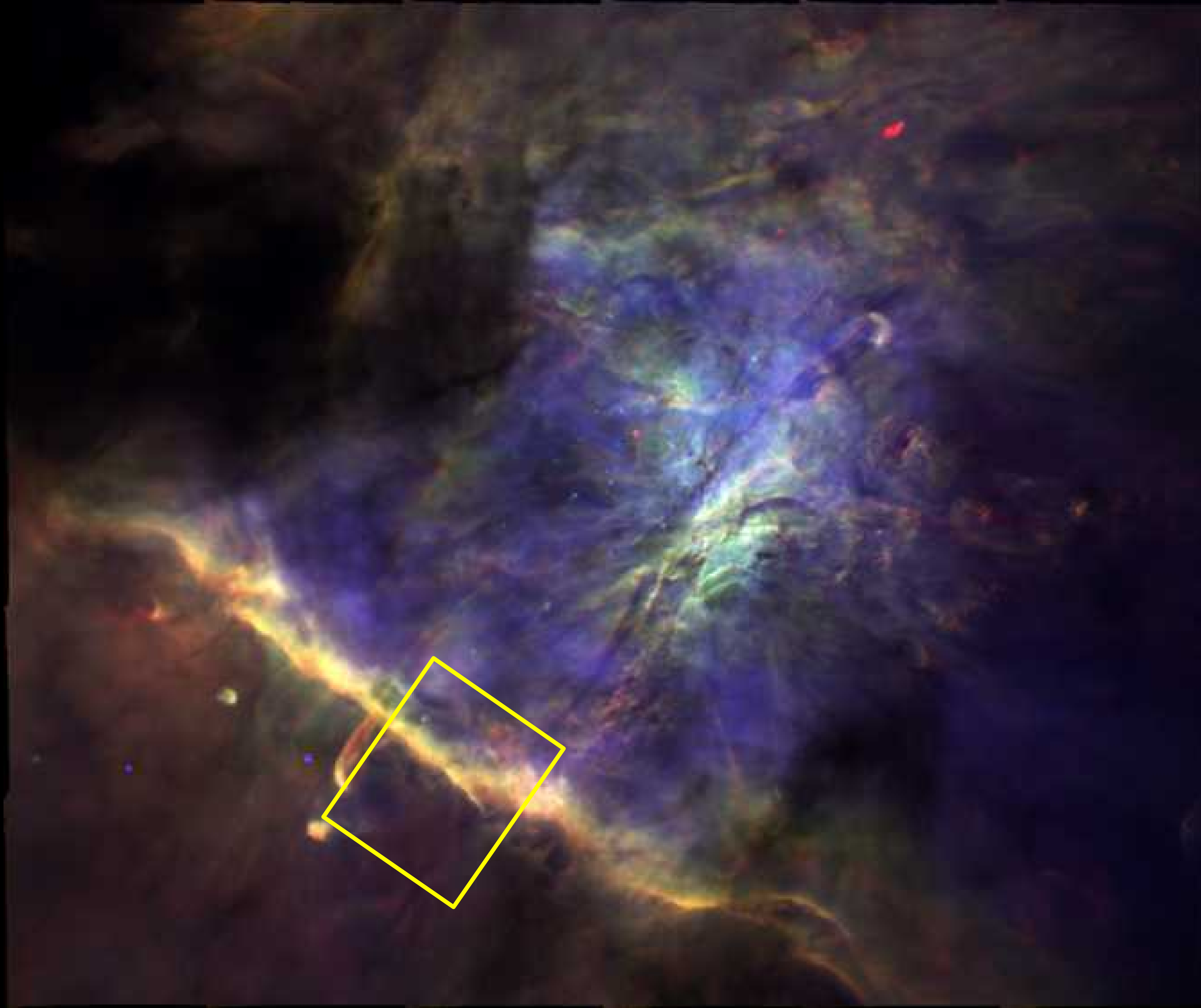
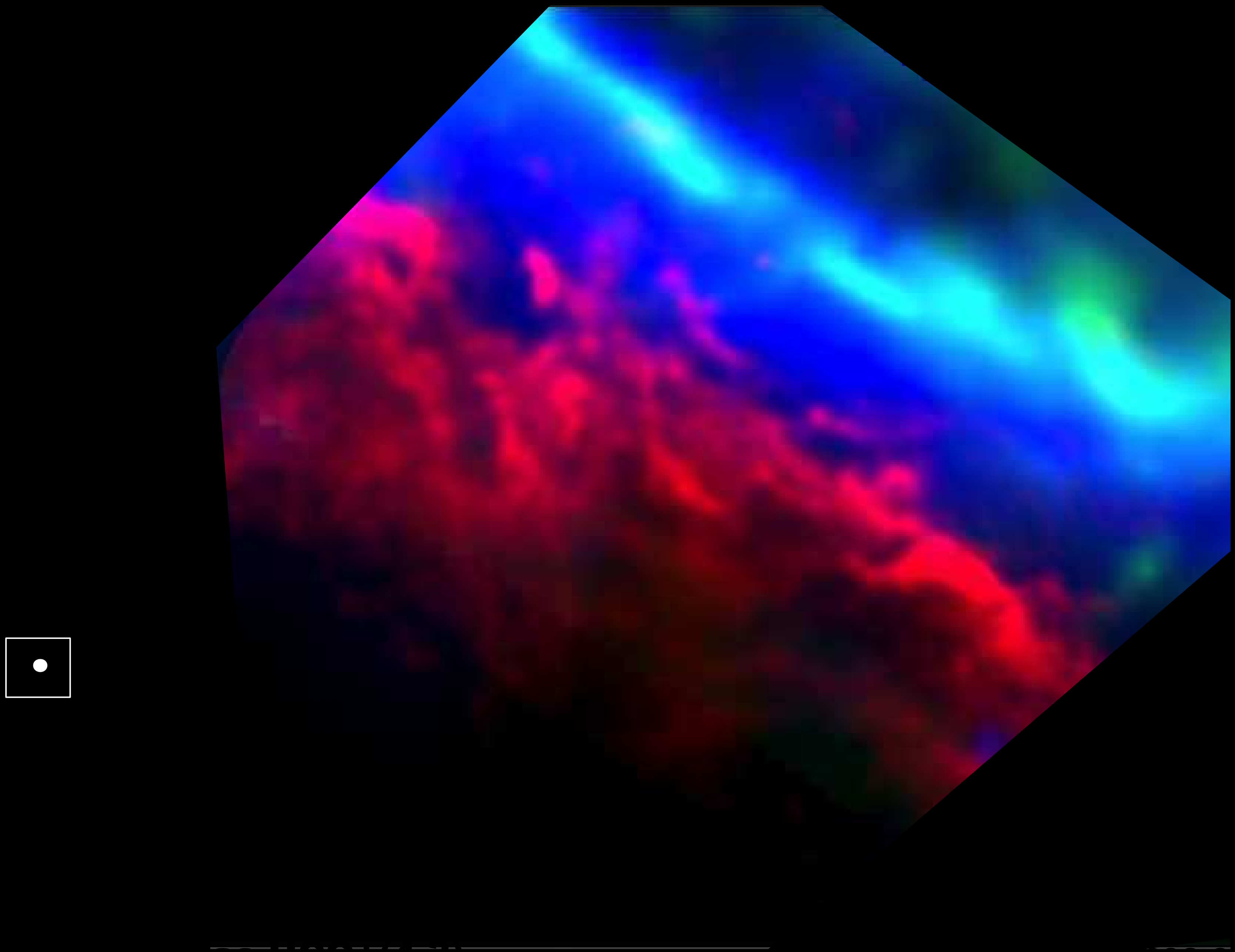


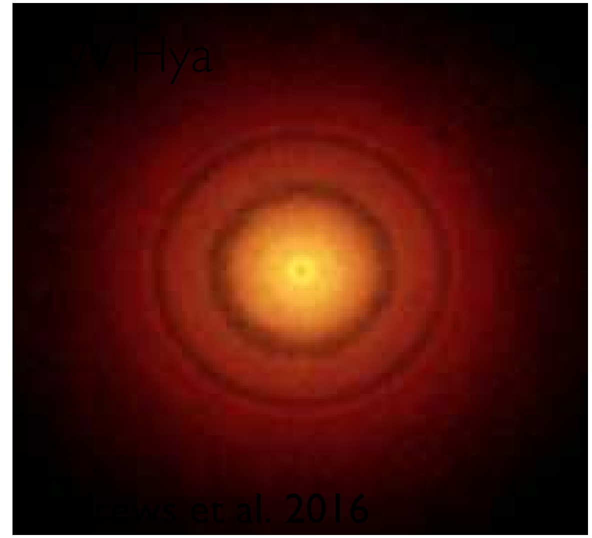
Plunkett et al. 2015 Nature 527,

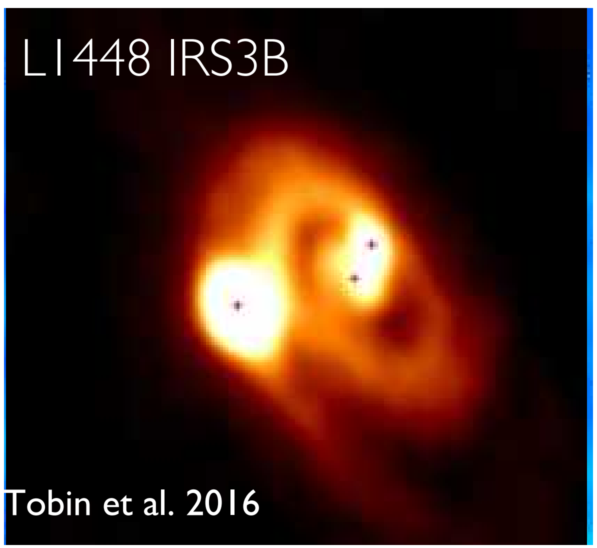


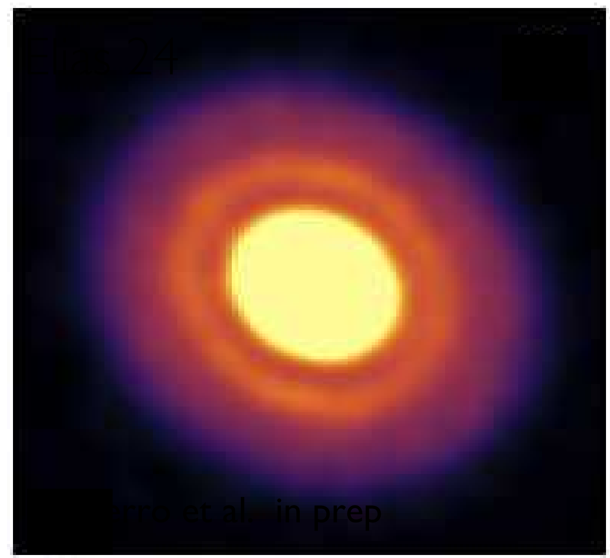


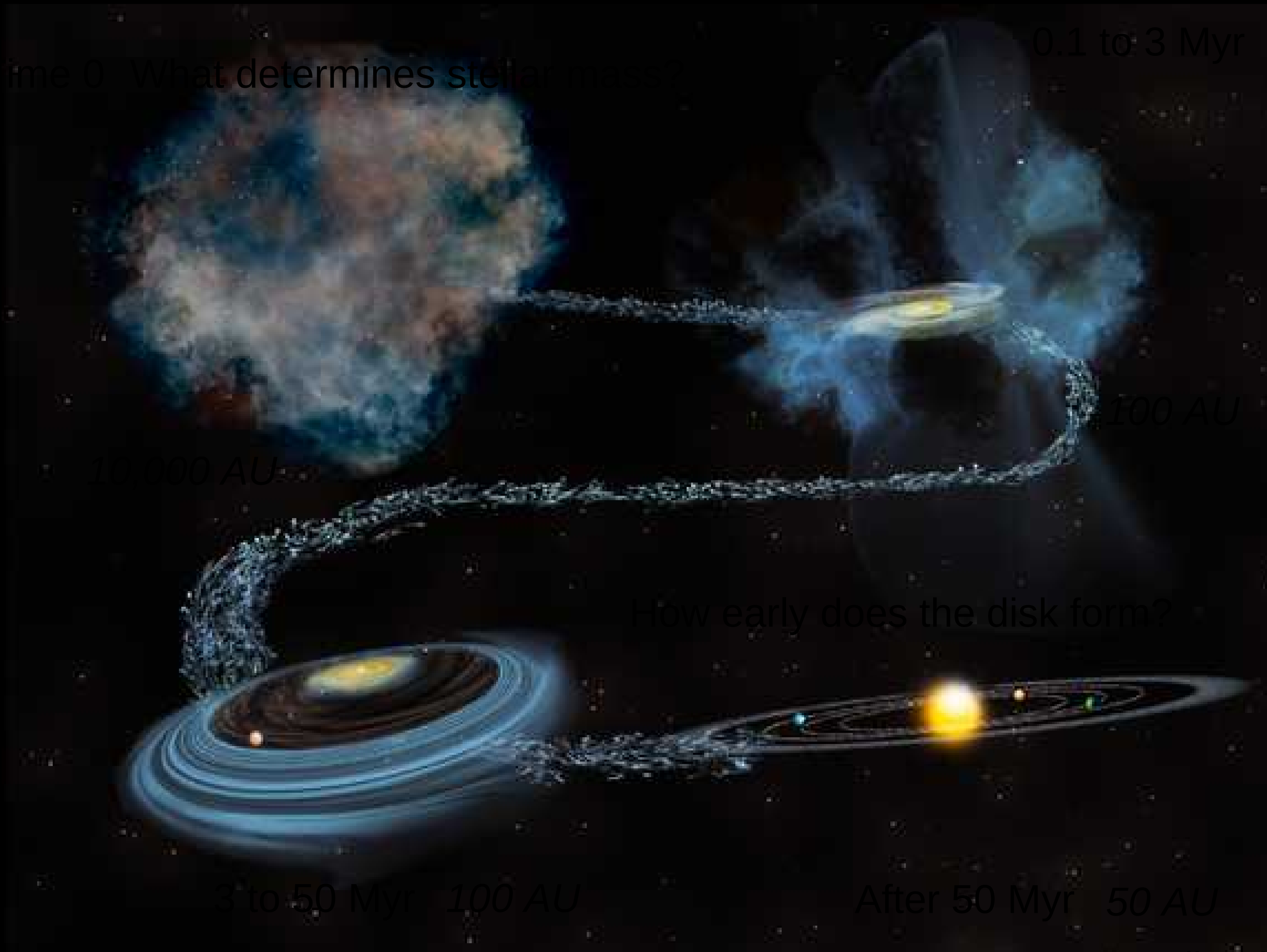







L1448 IRS3B
Tobin et al. 2016





What determines stellar mass?
0.1 to 3 Myr
100 AU
10,000 AU
How early does the disk form?
3 to 50 Myr
100 AU
After 50 Myr
50 AU

A Few Questions on Star Formation in Galaxies

- The Gas Supply: What sets the amount of molecular gas in different regions of galaxies? How is it (re)-arranged by galaxy dynamics?
- The Star-Forming Gas Supply: How is the reservoir of molecular gas structured? Is all molecular gas in a ‘star-forming’ bound cloud phase?
- The Properties of Clouds: What internal properties of clouds govern their star formation efficiency? What controls those properties?
- The Evolution of Clouds & Feedback: How

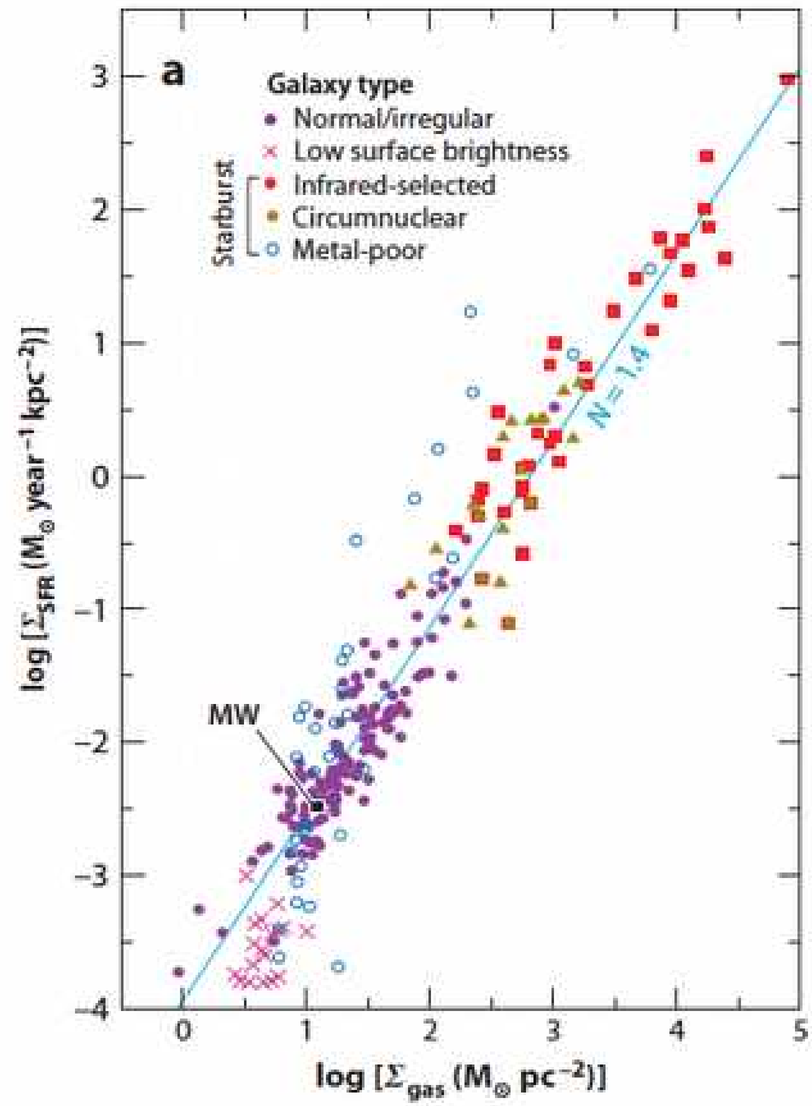
- High angular resolution
- Sensitivity/High dynamical range
- Gas mass tracers
- Define cloud properties
- Detailed views spanning large range of scales

Star Formation Relationship: Kennicutt-Schmidt Law

- Relationship between the disk-averaged surface densities of star formation and gas (HI and H2) for different classes of star-forming galaxies.
- For each point (individual galaxy) the SFRs and gas masses have been normalized to the radius of the main star-forming disk.
- The blue line shows the relation with N=1.4 slope

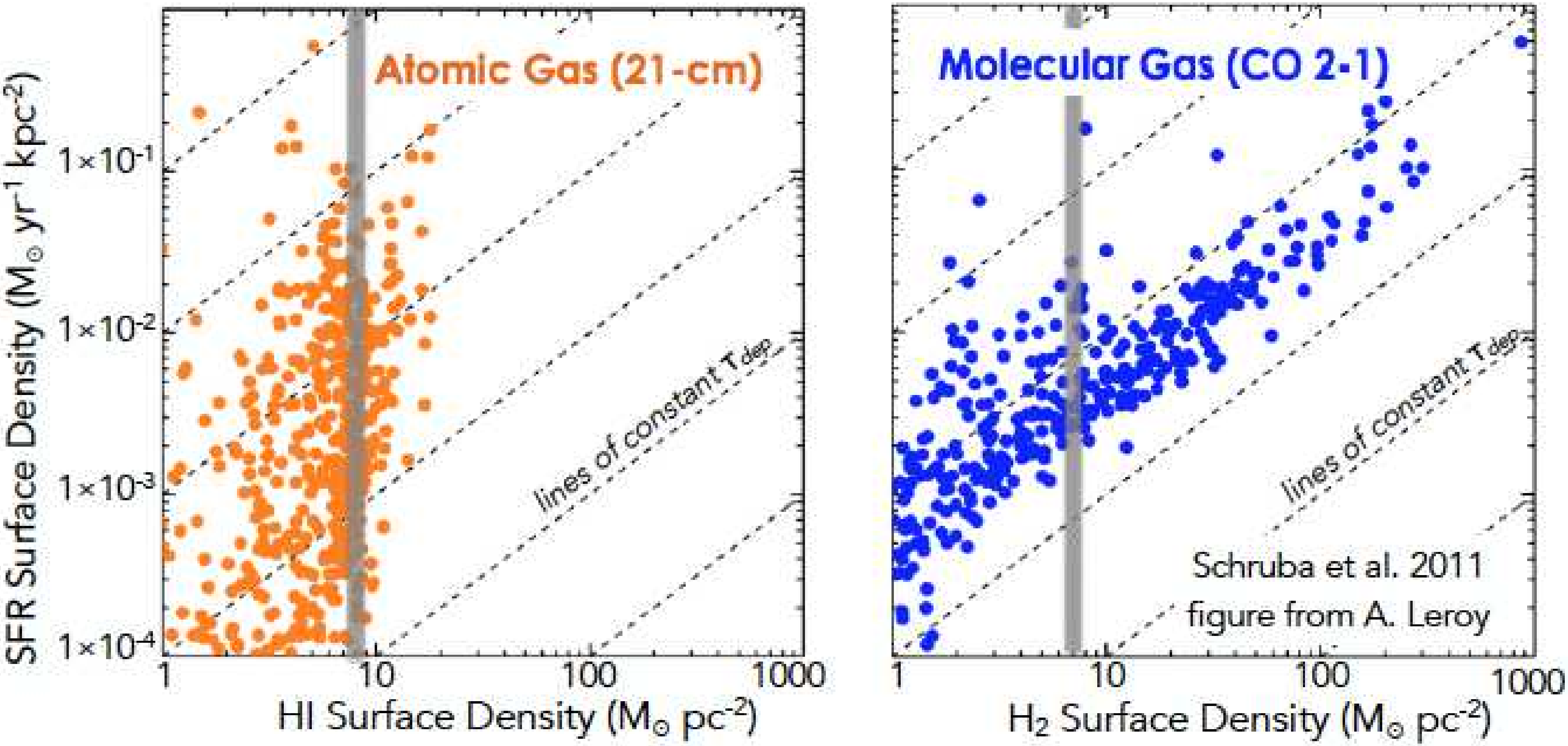
$$\varsigma_{SFR} = (2.5 \pm 0.7) x 10^{24} \left(\frac{\varsigma_{gas}}{M_{Sun} pc^{22}} \right)^{1.4 \pm 0.15} M_{Sun} yr^{21} kpc^{22}$$

- 'Surprisingly tight correlation of the global star formation law, extending over several orders of magnitude in SFR and gas density.'



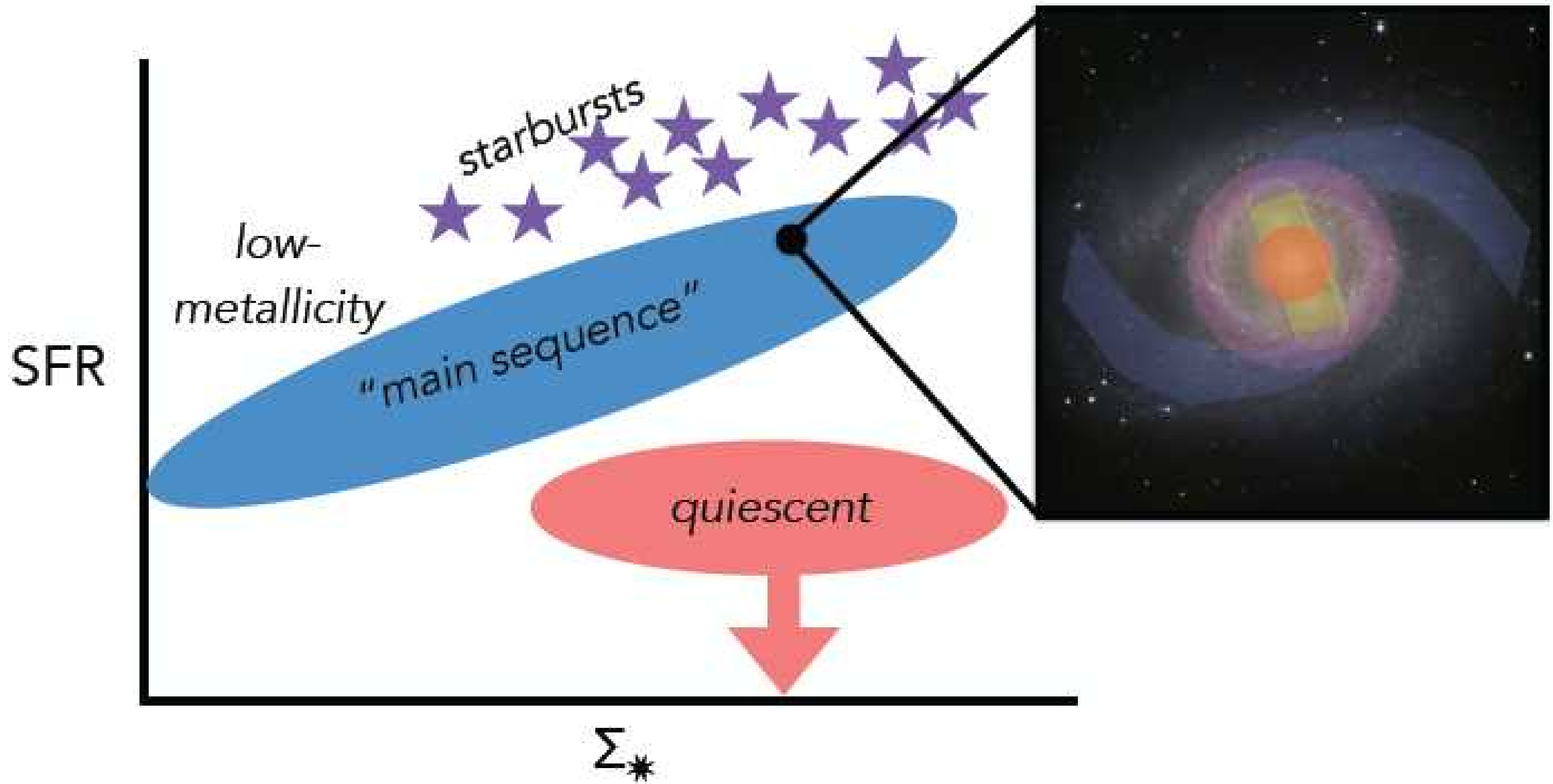
Kennicutt (1998) ApJ 498, 541; Kennicutt & Evans (2012) AARA 50, 531

Star Formation Occurs in Molecular Gas



- *Except possibly in very low metallicity conditions*

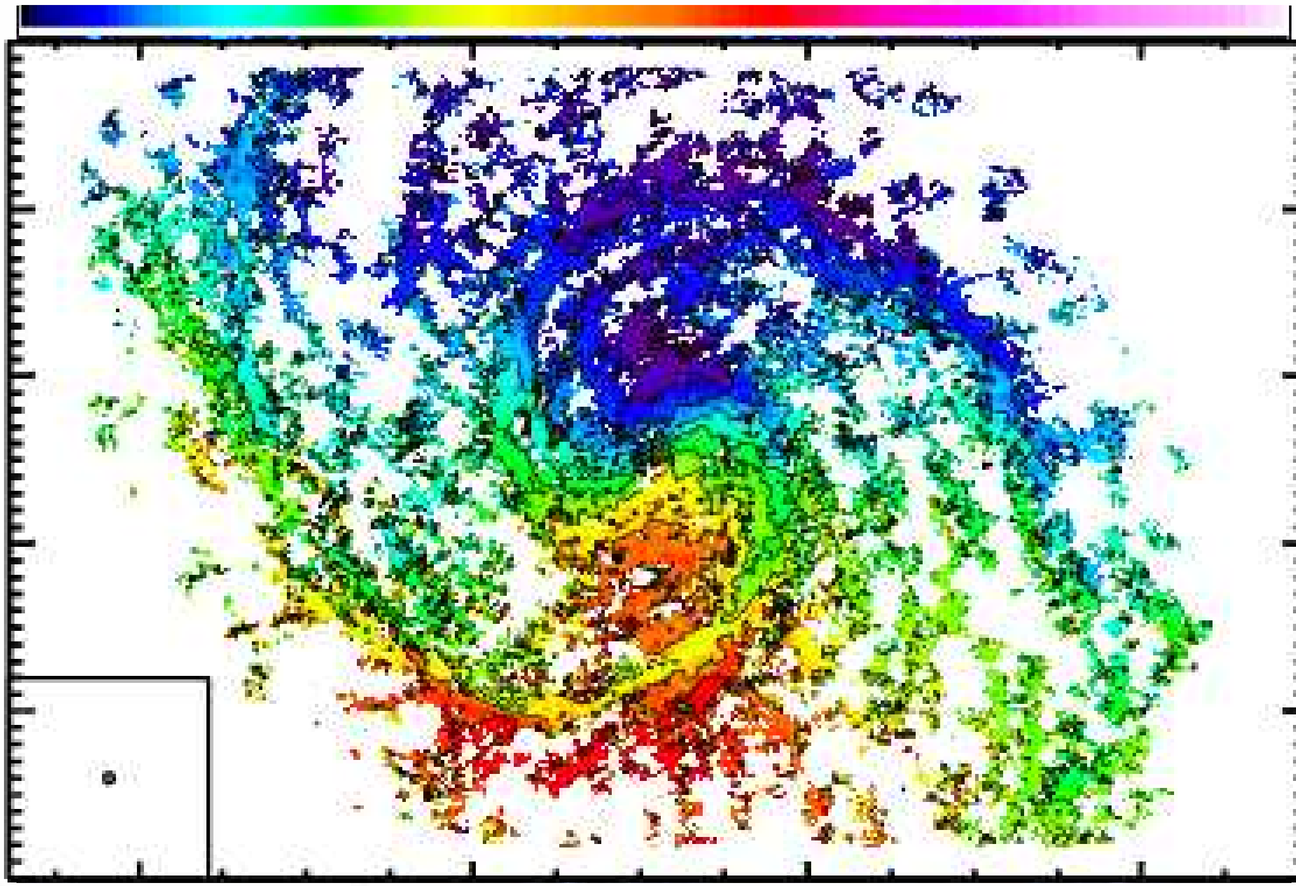
Systematic Variations in SFR to Gas



Correlated with galaxy properties and environments within a Galaxy

A High-Spatial Resolution CO Survey of M51

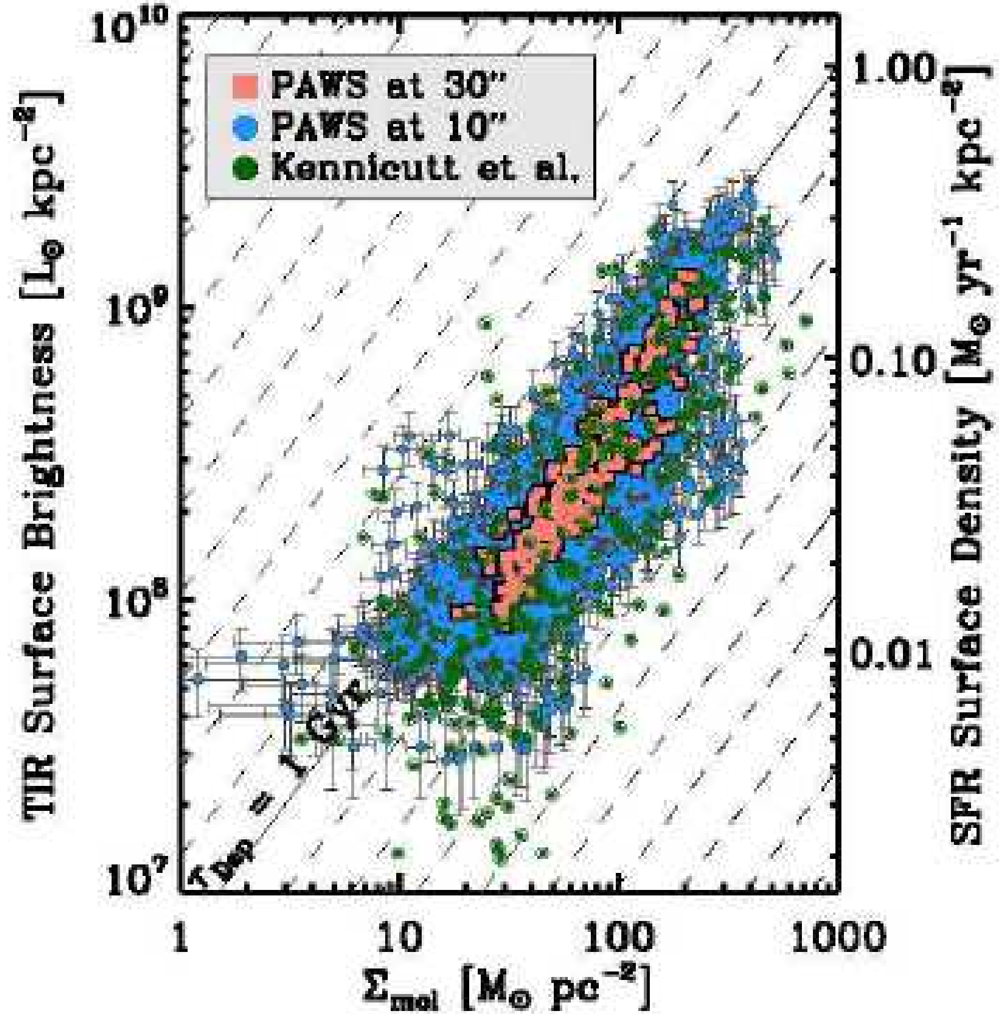
- High resolution (40 pc) imaging in CO(1-0) in central 9 x 6 kpc region of M51 using the PdBI and 30-meter telescope
- Structure of the turbulent ISM at the scale of individual giant molecular clouds
- Combining with infrared maps from Herschel and Spitzer, one can measure how the cloud-scale structure of the ISM relates to the galaxy's ability to form stars



Schinnerer et al. (2015) – PAWS Large Program with the PdBI/30-meter

Cloud Scale Structure and Star Formation in M51

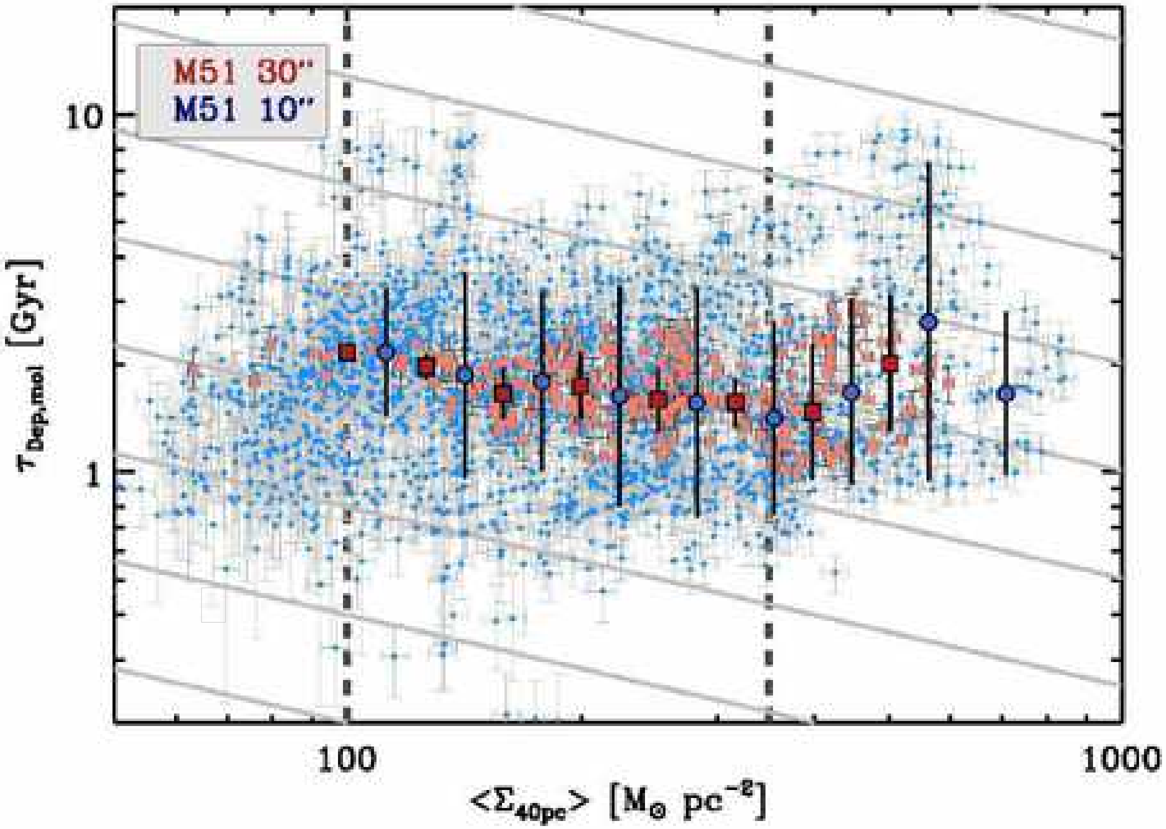
- IR-CO scaling relations in M51 over the whole galaxy (a) and the PAWS field (b)
- Diagonal lines indicate fixed molecular gas depletion times (spaced by factors of 2). Overall *τDep* ≈ 1.5 Gyr
- More scatter in the CO-to-IR ratio is visible at high resolution with both high and low depletion times at gas densities > 100 M⊙ pc-2
- Related to evolution of or changes in local structure of the gas individual in star-forming clouds, e.g. gas-rich regions that are IR-weak could trace clouds where streaming motions suppress the collapse of gas.



Leroy, Schinnerer et al. (2017) in press

Cloud Scale Structure and Star Formation in M51

- The dynamical state of the gas as traced by *b*r Σmol/σ2, the *boundedness parameter*, i.e. the ratio of potential energy to kinetic energy.
- When *b* is high, the gas should be more gravitationally bounded.



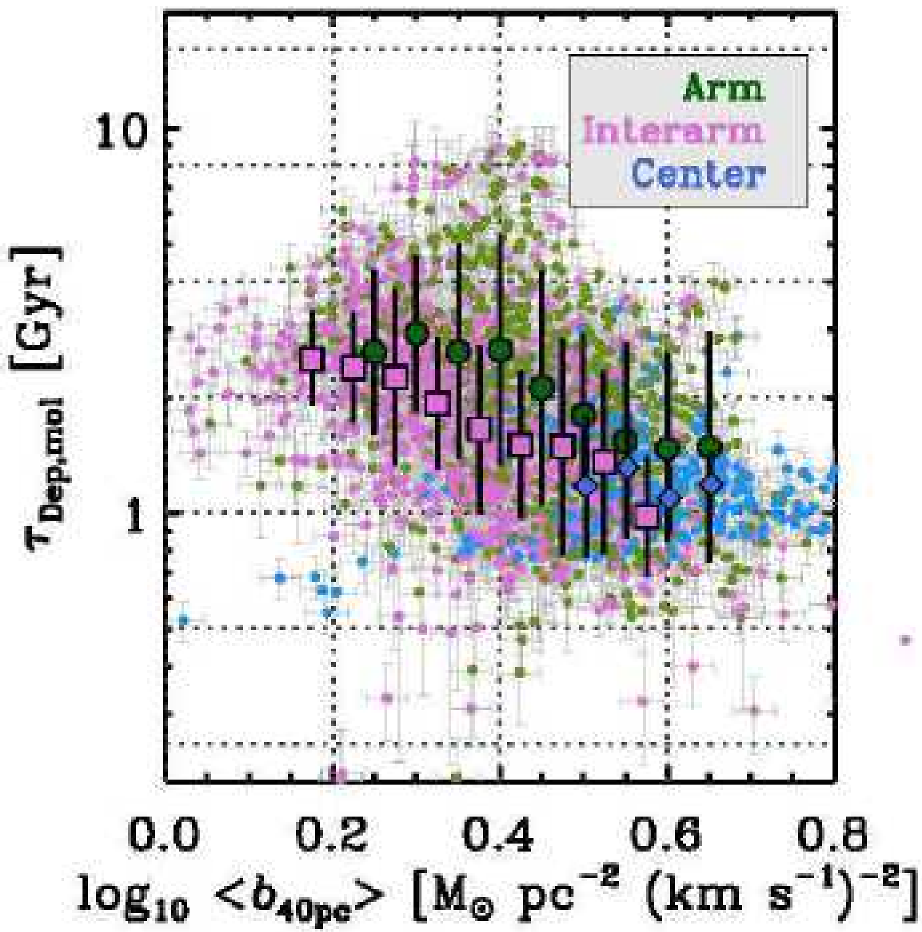
- High surface density gas should be denser, with a shorter collapse time
- The molecular gas depletion time is shown as a function of cloud surface density
- In the range 100 to 350 M⊙ pc-2 a mild anti-correlation is seen indicating that denser gas form stars at a higher rate.

Leroy, Schinnerer et al. (2017)

- At higher surface density gas tends to form stars less efficiently

Cloud Scale Structure and Star Formation in M51

- The depletion time τDep appears most closely related to the boundedness parameter (both in the arm and interarm regions).
- Gas with stronger self-gravity (higher *b*) forms stars at a higher rate (low τDep)
- Note however the overlap in τDep of different regions of M51 pointing to a variety of conditions and star forming efficiencies across the galaxy.



Leroy, Schinnerer et al. (2017)

NGC1068 – The Complex Centre as seen by ALMA

- High resolution (20-35 pc) imaging at 0.8 mm of dust and molecular species in the central 2 kpc NGC 1068 (*and in CO(6-5) with 4 pc resolution*)
- Molecular lines and dust detected from the CND, the 2.6 kpc bar region and the 1.2 kpc starburst ring
- The inner rotation is perturbed by an inward radial flow in the SB ring and bar region
- A massive outflow revealed by the kinematics from r~50 to 400 pc which is AGN

Takano et al. (2015) – ALMA observations of HC3N (yellow), CS (red) and CO (blue) in the central 4.3 kpc superimposed on HST image

NGC1068 – Overall Dynamics

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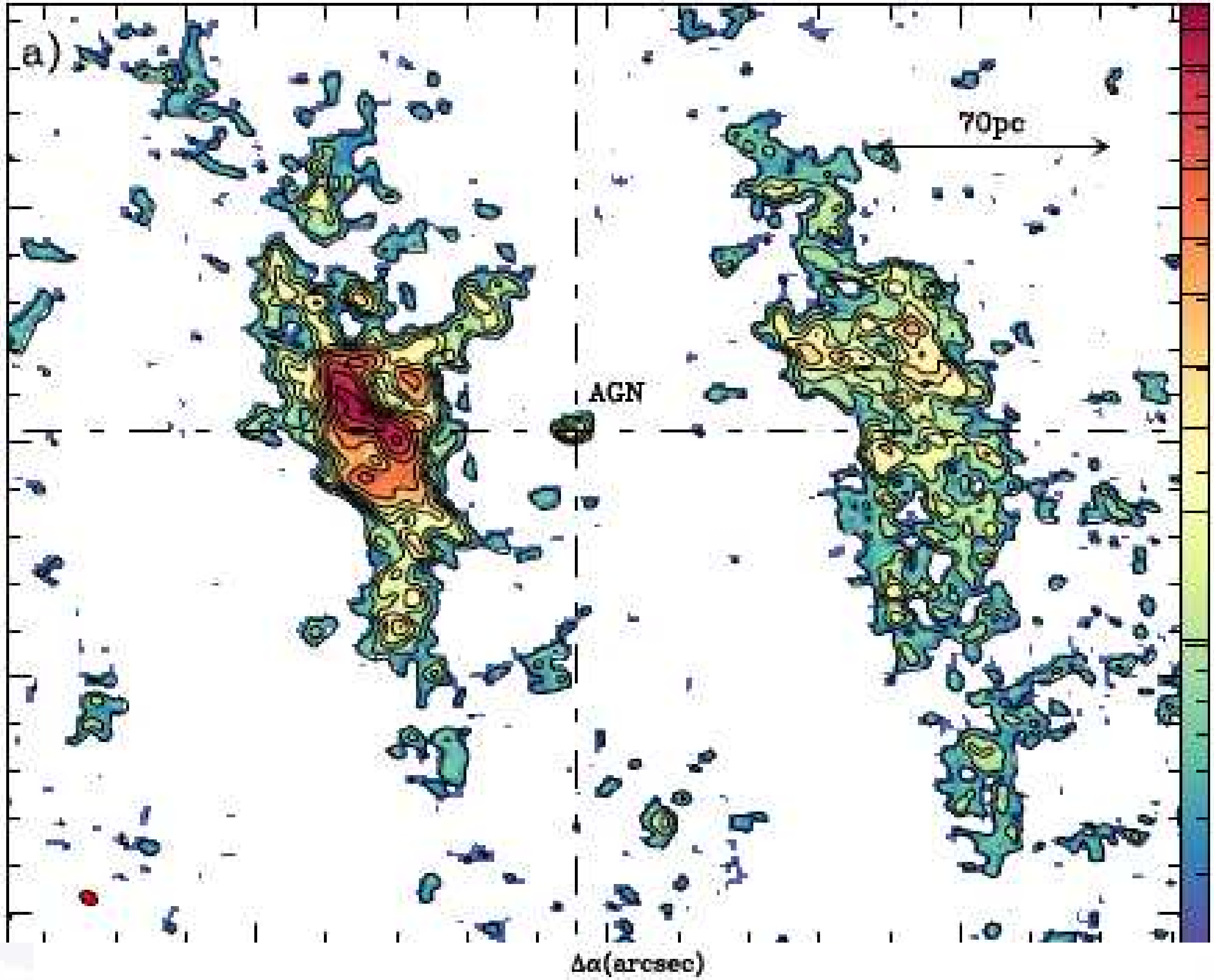
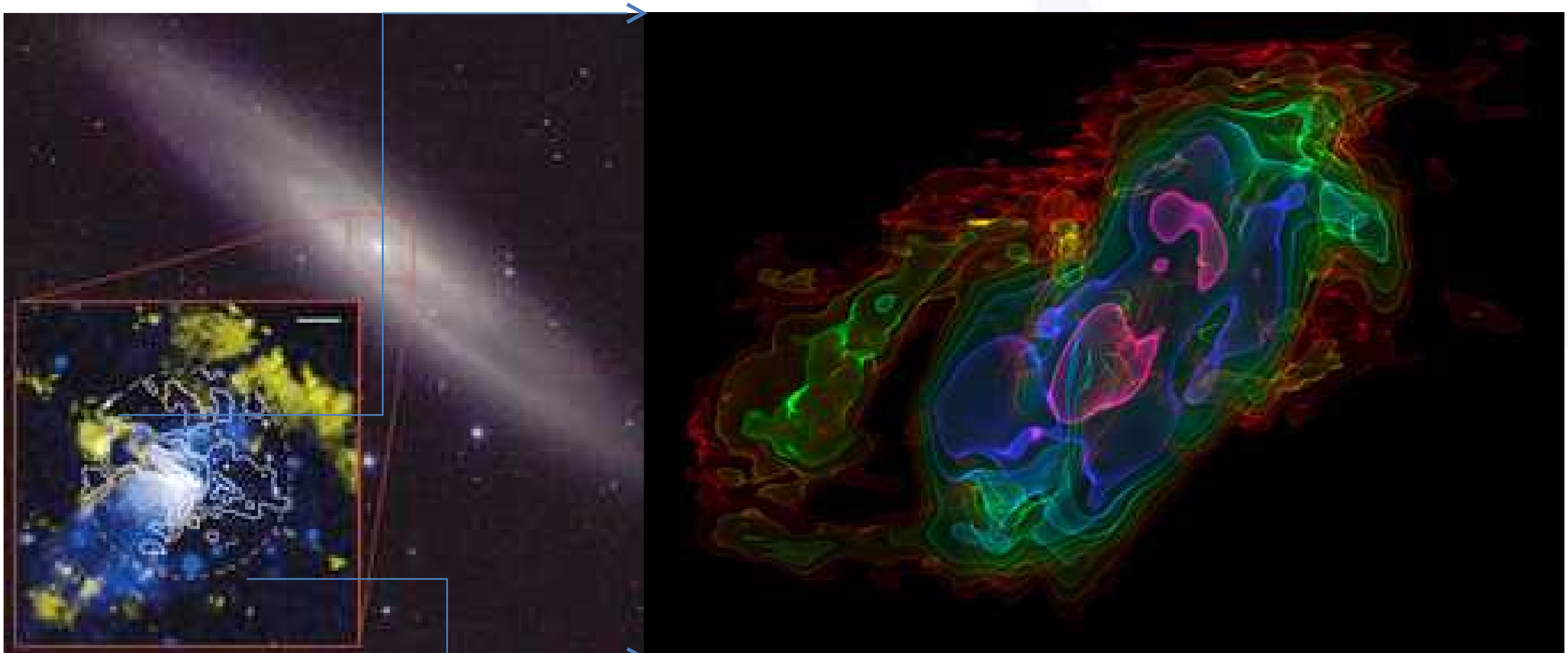


Garcia-Burillo et al. (2015) A&A 567, 125 and (2016) *ApJ 823, L12*

Suppression of Star Formation in NGC 253

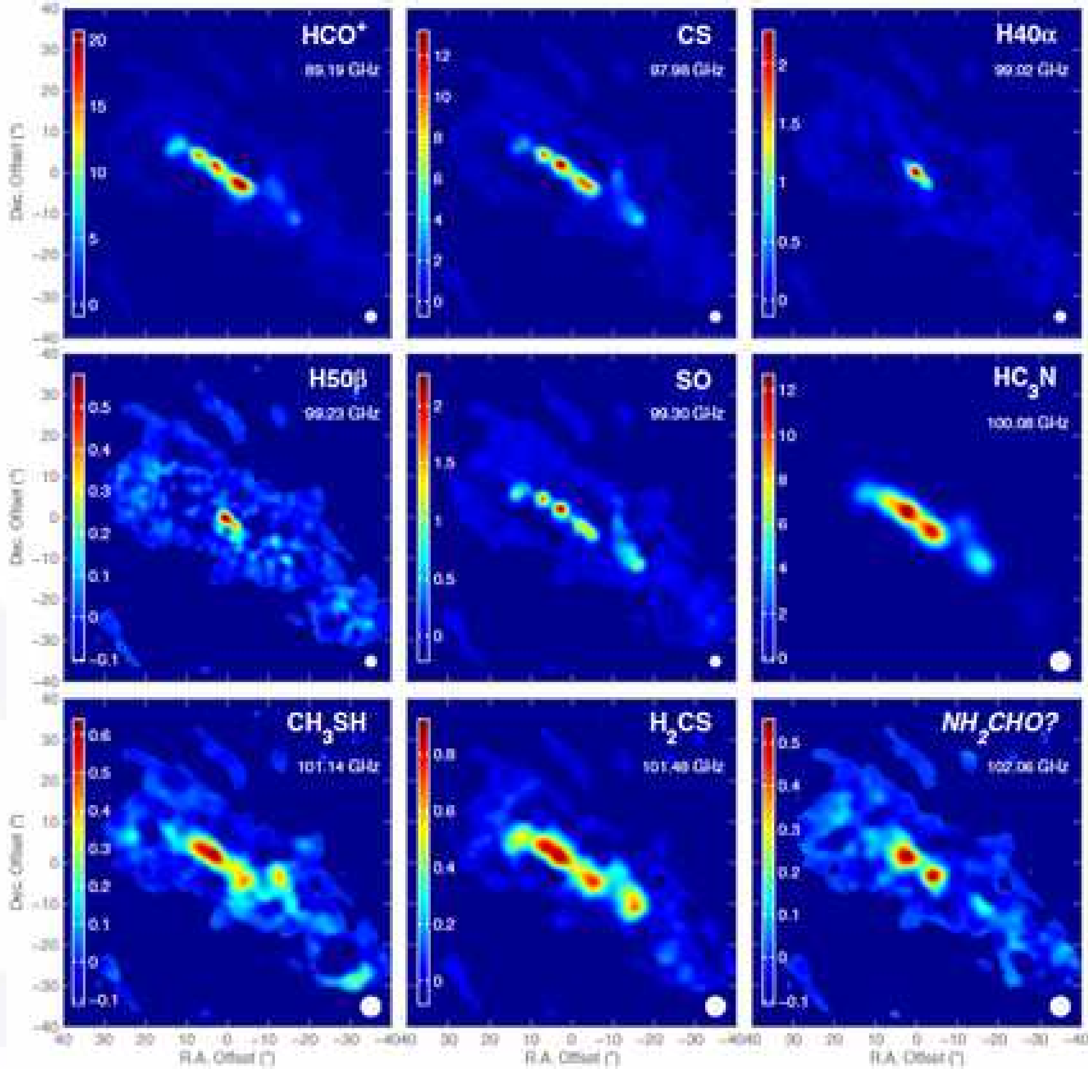
- Starburst-driven molecular wind
- Molecular outflow rate is greater than 3 – 9 Msun/yr
- Starburst-driven wind limits the star-formation activity



Bolatto et al., 2013, Nature 499, 450

Multi-Line Imaging in NGC 253

- High resolution (50 pc) imaging at 3 mm of molecular species in NGC 253
- A total of 50 lines are detected over a 13 GHz bandwidth; 27 identified, 13 tentative
- Molecular richness, including tentative detections of aldehydes, cyanides and other complex organics
- Mapping the various regions of the nucleus (PDR, dense gas, shocks, outflows) and their interactions



Meier et al. (2015) ApJ 801, 63

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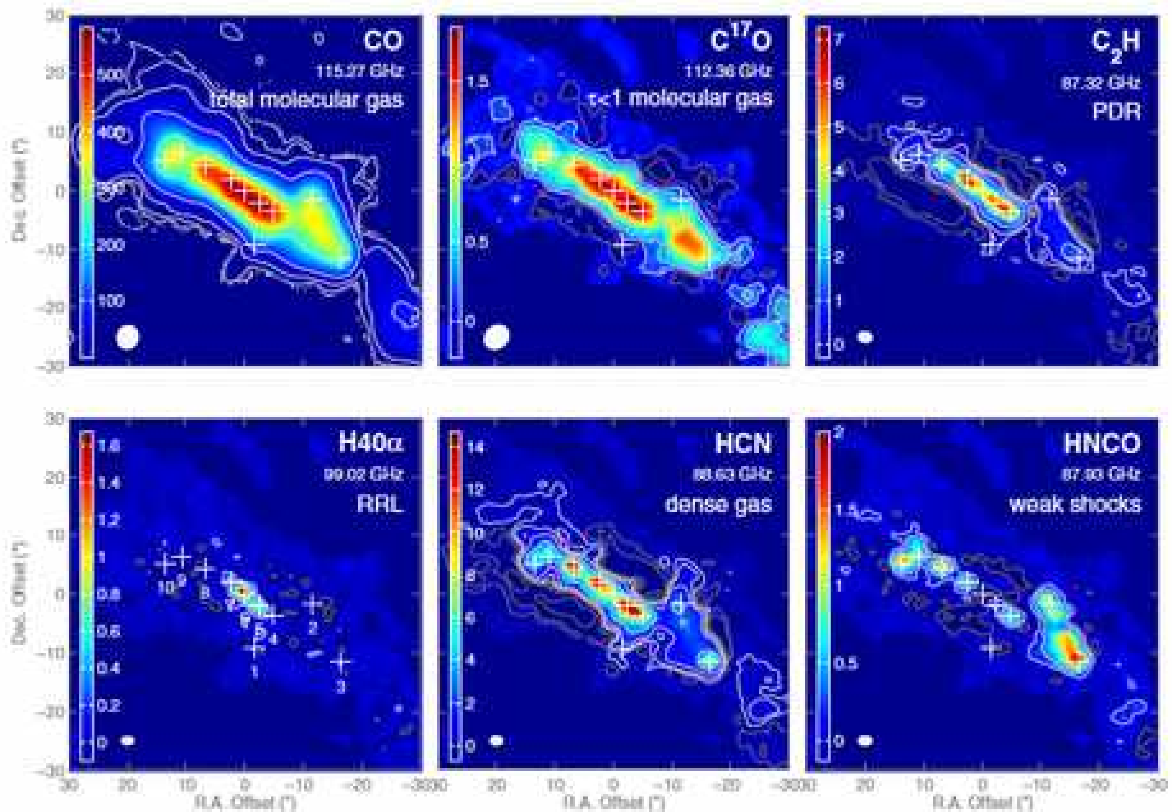
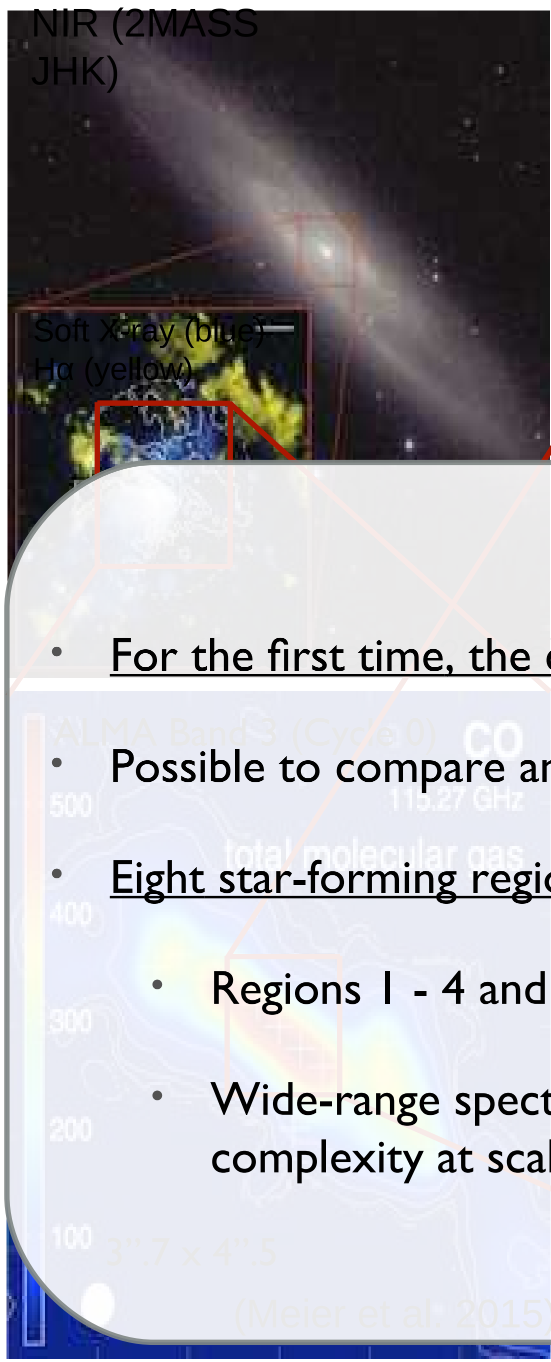
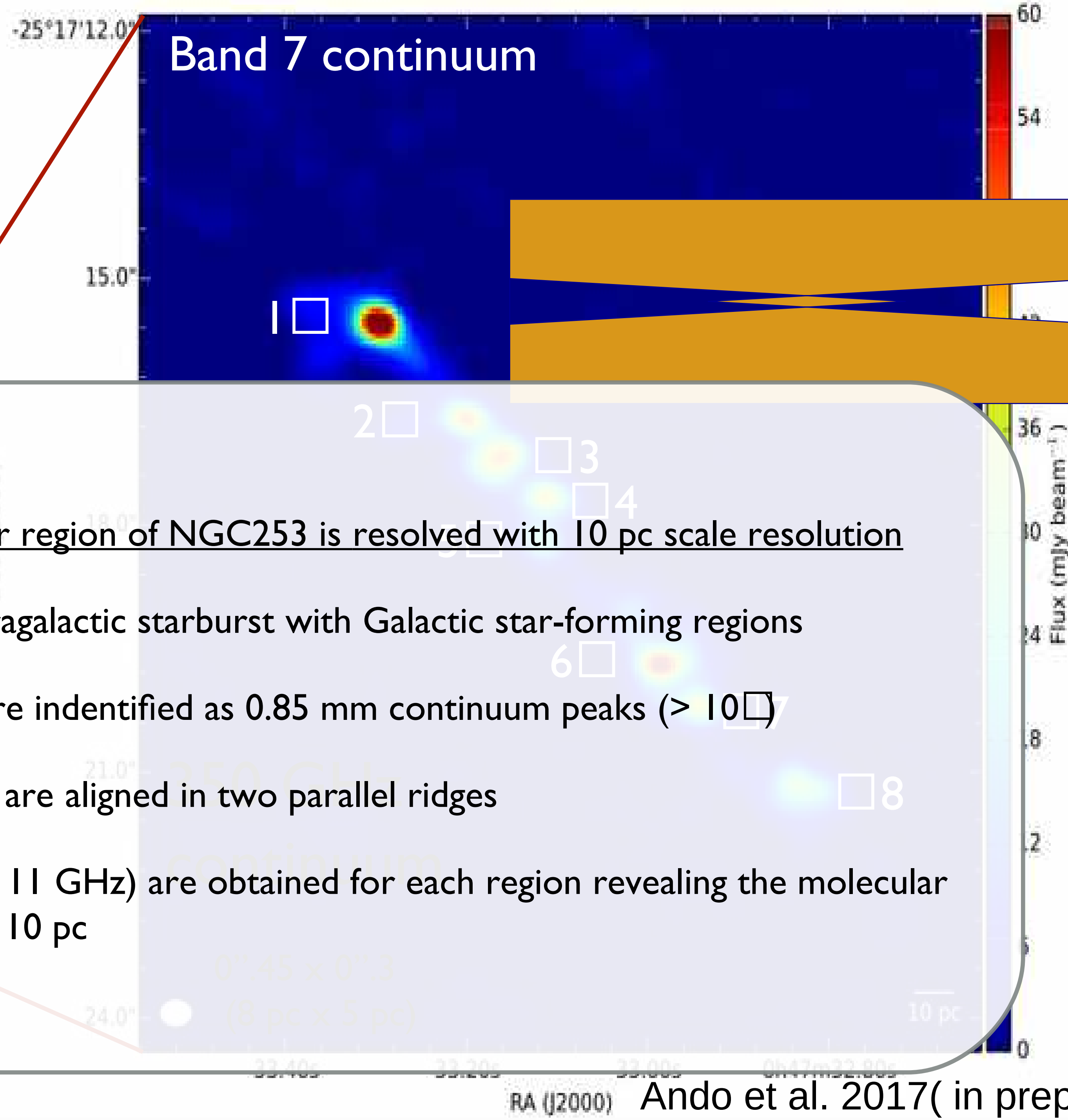


Meier et al. (2015) ApJ 801, 63

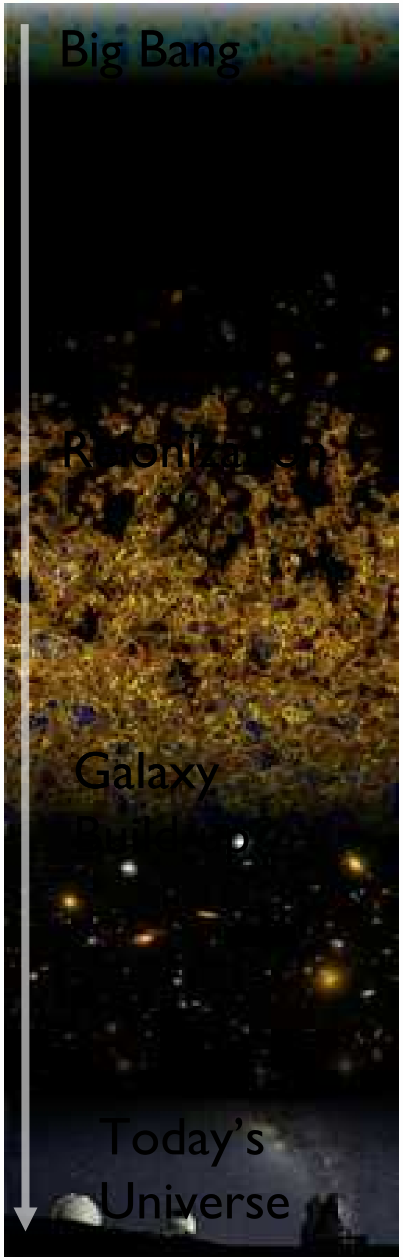




- <u>For the first time, the center region of NGC253 is resolved with 10 pc scale resolution</u>
- Possible to compare an extragalactic starburst with Galactic star-forming regions
- <u>Eight star-forming regions</u> are indentified as 0.85 mm continuum peaks (> 10□)
  - Regions 1 - 4 and 5 - 8 are aligned in two parallel ridges
  - Wide-range spectra (~ 11 GHz) are obtained for each region revealing the molecular complexity at scales of 10 pc

Ando et al. 2017(in prep)

Probing the Early Universe



z~1000
0.0003 Gyr

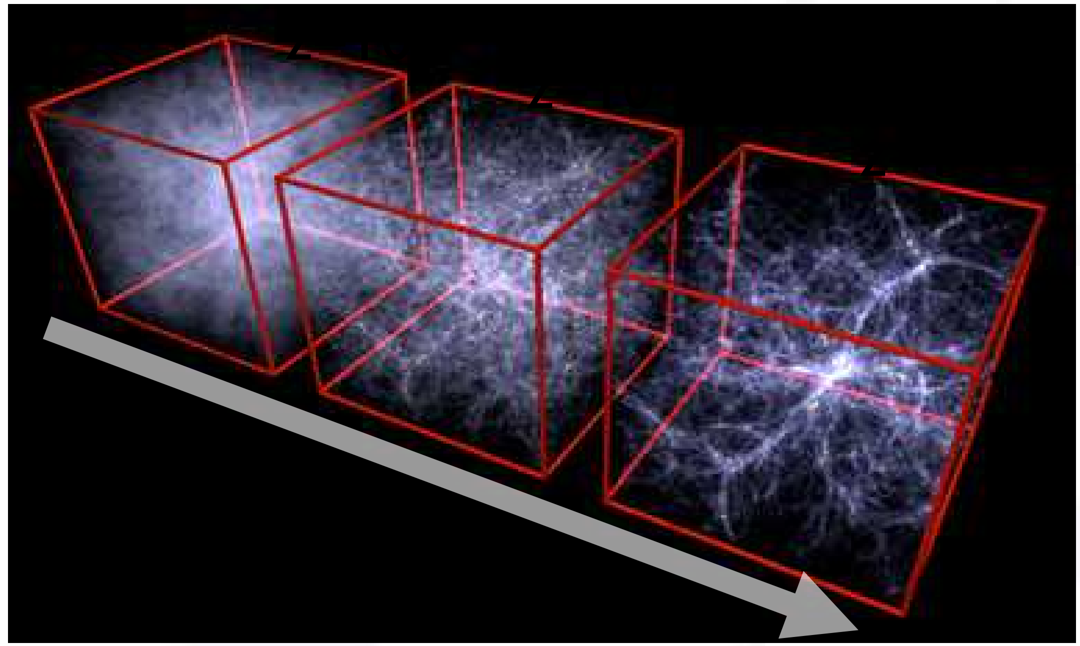
z~15-1000
0.0003-0.3 Gyr

z~8-15
0.3-1 Gyr

z<~8
>1 Gyr

z~0
14.3 Gyr

Simulations of structure formation



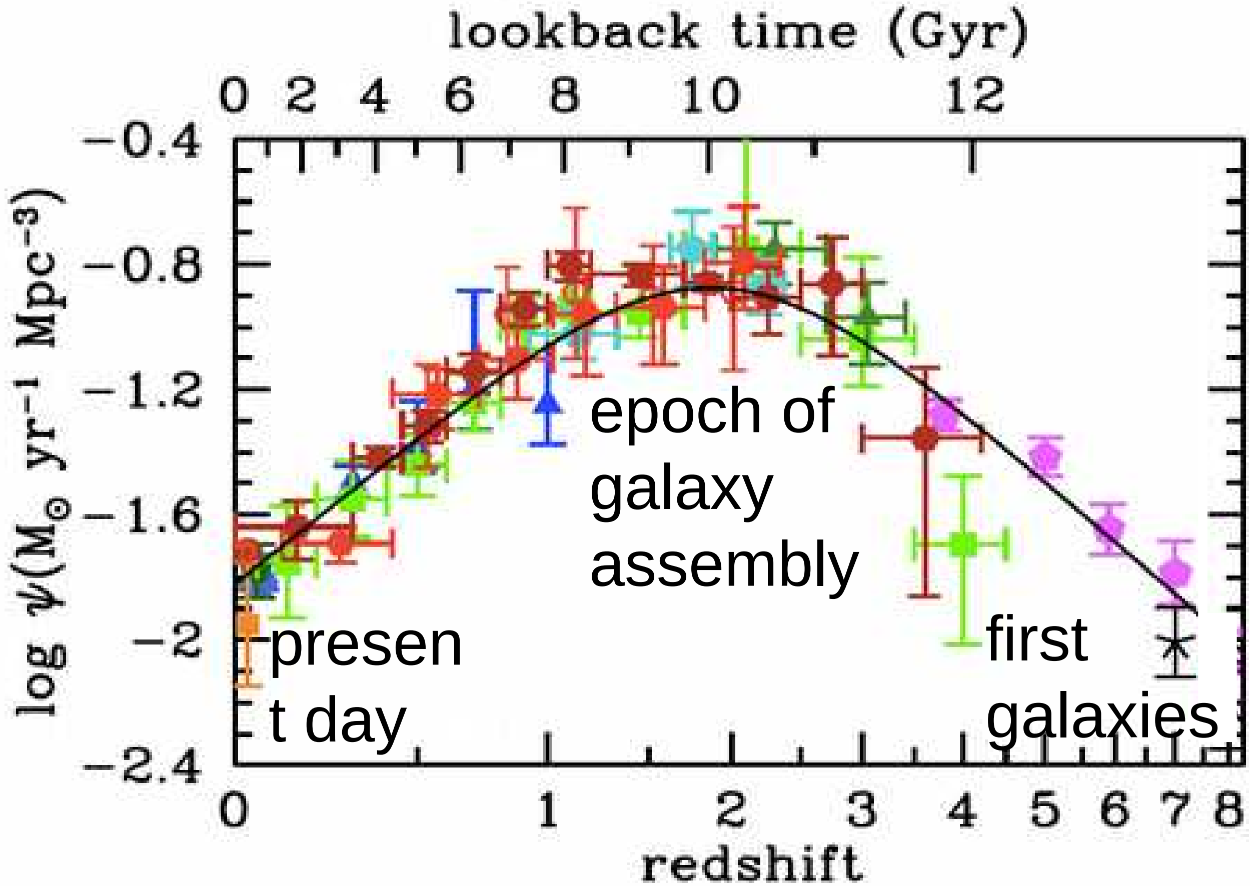
e.g., Springel et al.

Galaxies grow through gas accretion...

...but the gas supply is currently largely unconstrained observationally

Star Formation over Cosmic Time

Volume density of star formation in galaxies as f(cosmic time)

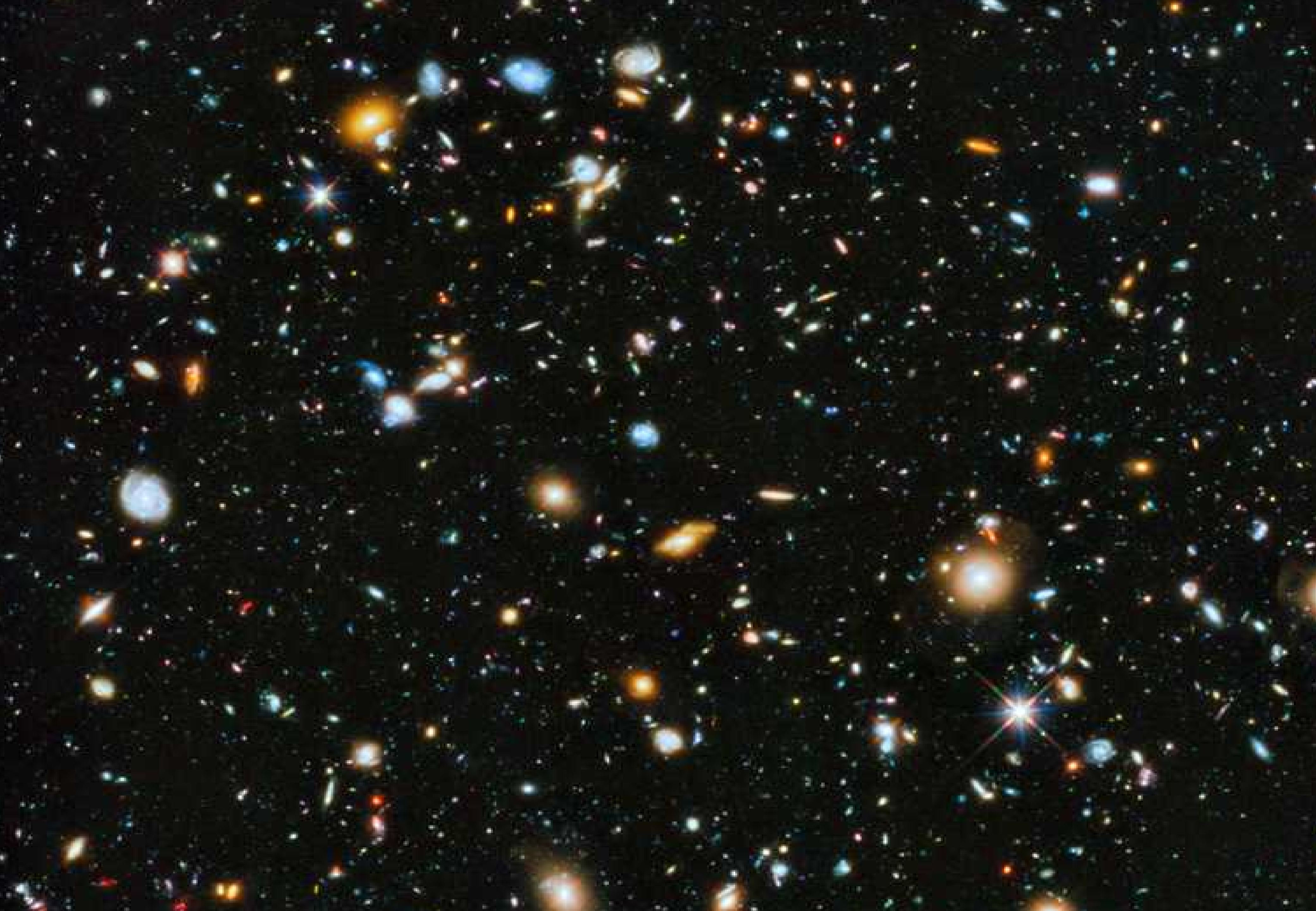


Madau & Dickinson, ARA&A 2014

what causes this evolution?

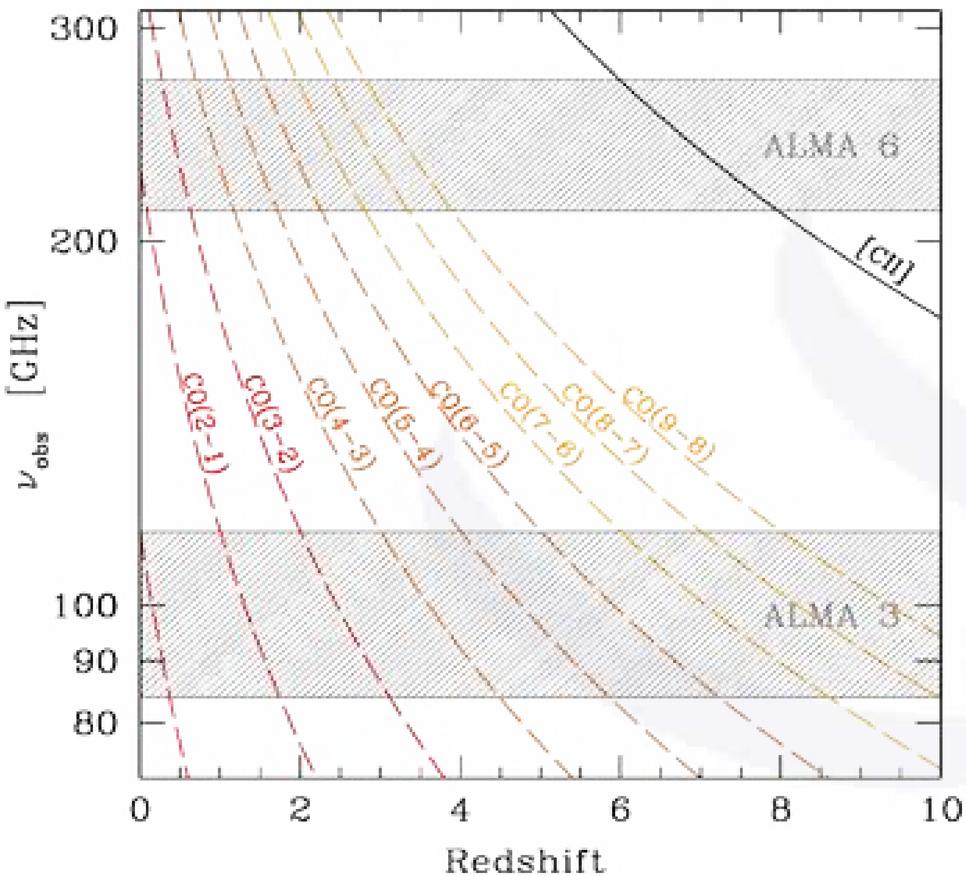
State of the Early Universe Studies with ALMA

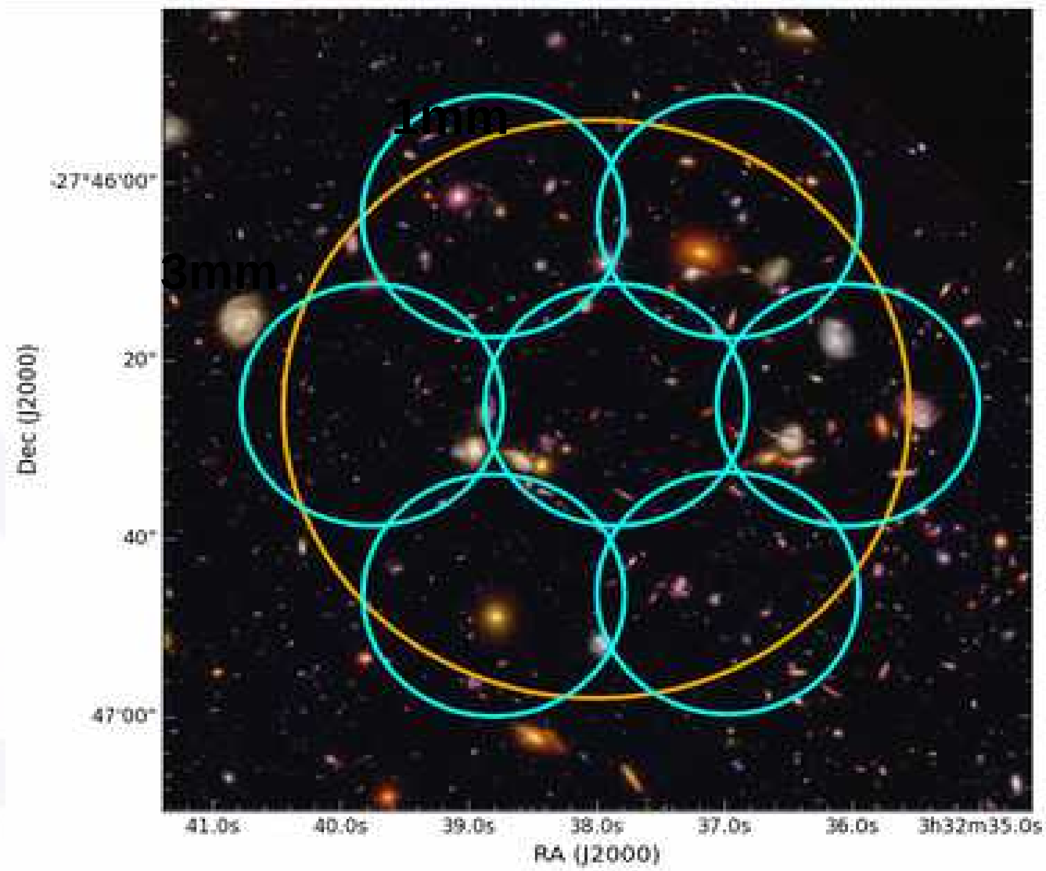
- ALMA dust pointed and blank continuum & line surveys providing statistical global and gas properties
- Together with the wealth of data from CO surveys from other facilities and Herschel surveys, a self-consistent picture of gas scaling is emerging
- Detailed studies of dusty sub-millimeter galaxies
- High-resolution & sensitivity observations of gravitationally amplified galaxies provide spectacular results and insights in the morphology of normal galaxies up to z~3
- Chemical complexity and other molecular and atomic tracers of the ISM at high-redshifts have resulted in new views of the processes at play.

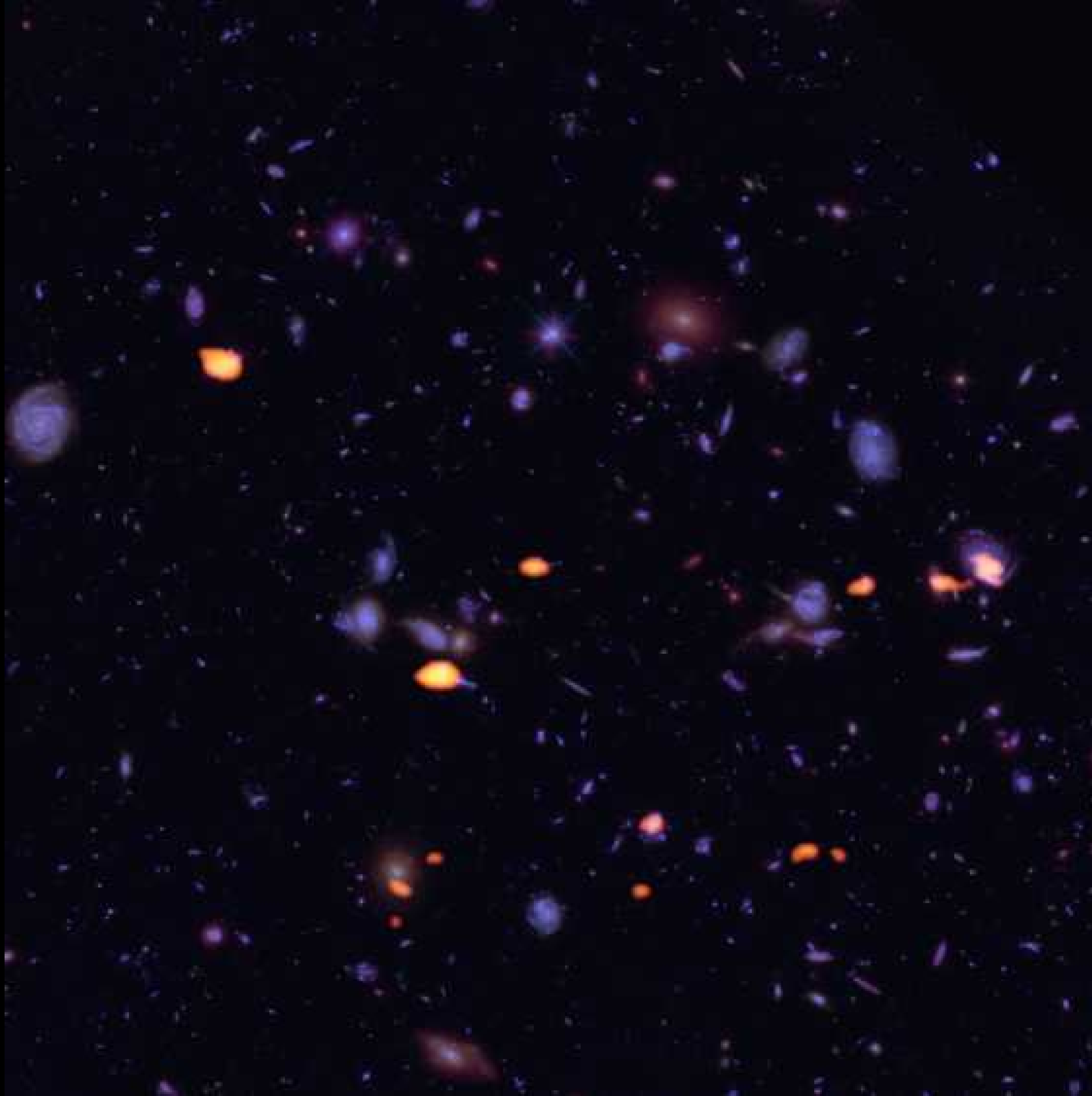


ALMA UDF: ASPECS Pilot Program

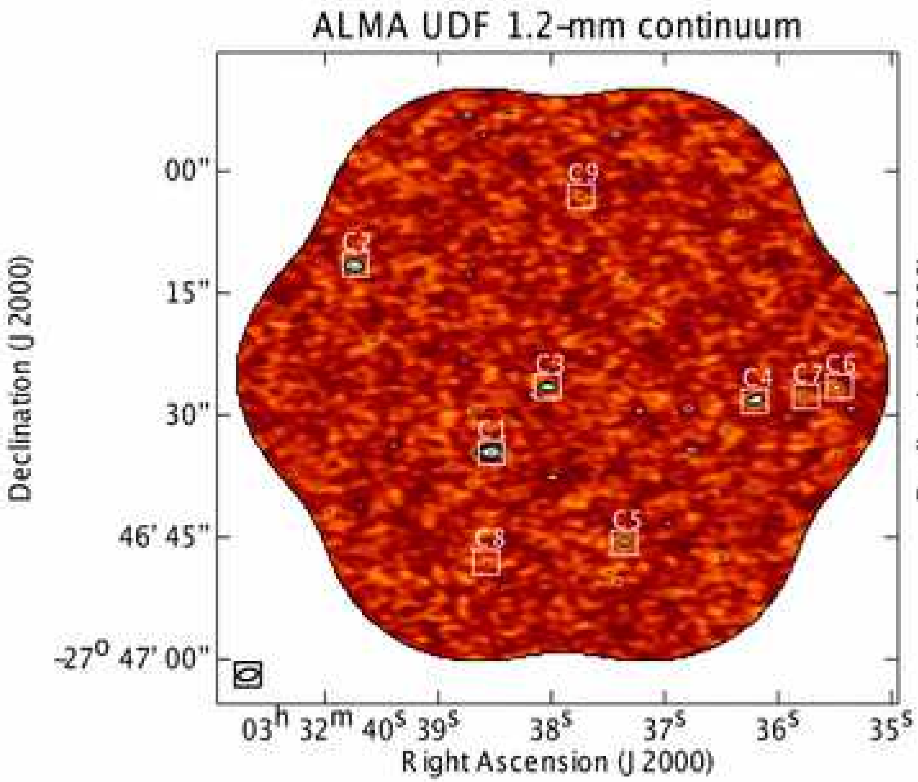
40h ALMA spectral scans in the UDF
(Aravena et al. & Walter et al. 2016):
complete CO coverage @ z>0, [CII] @ z=6-8

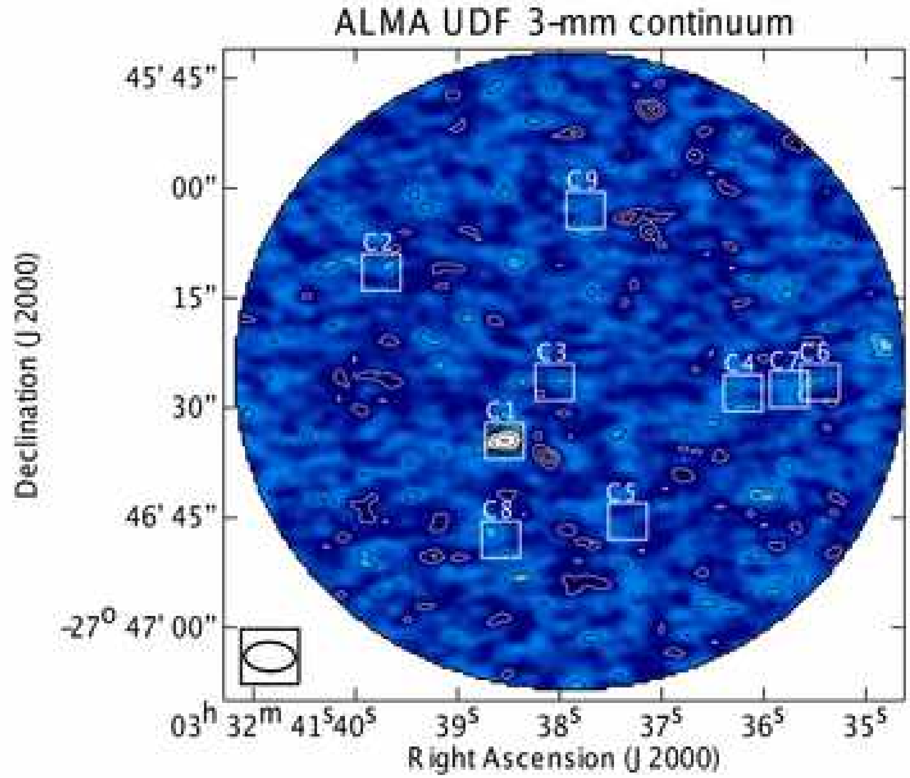






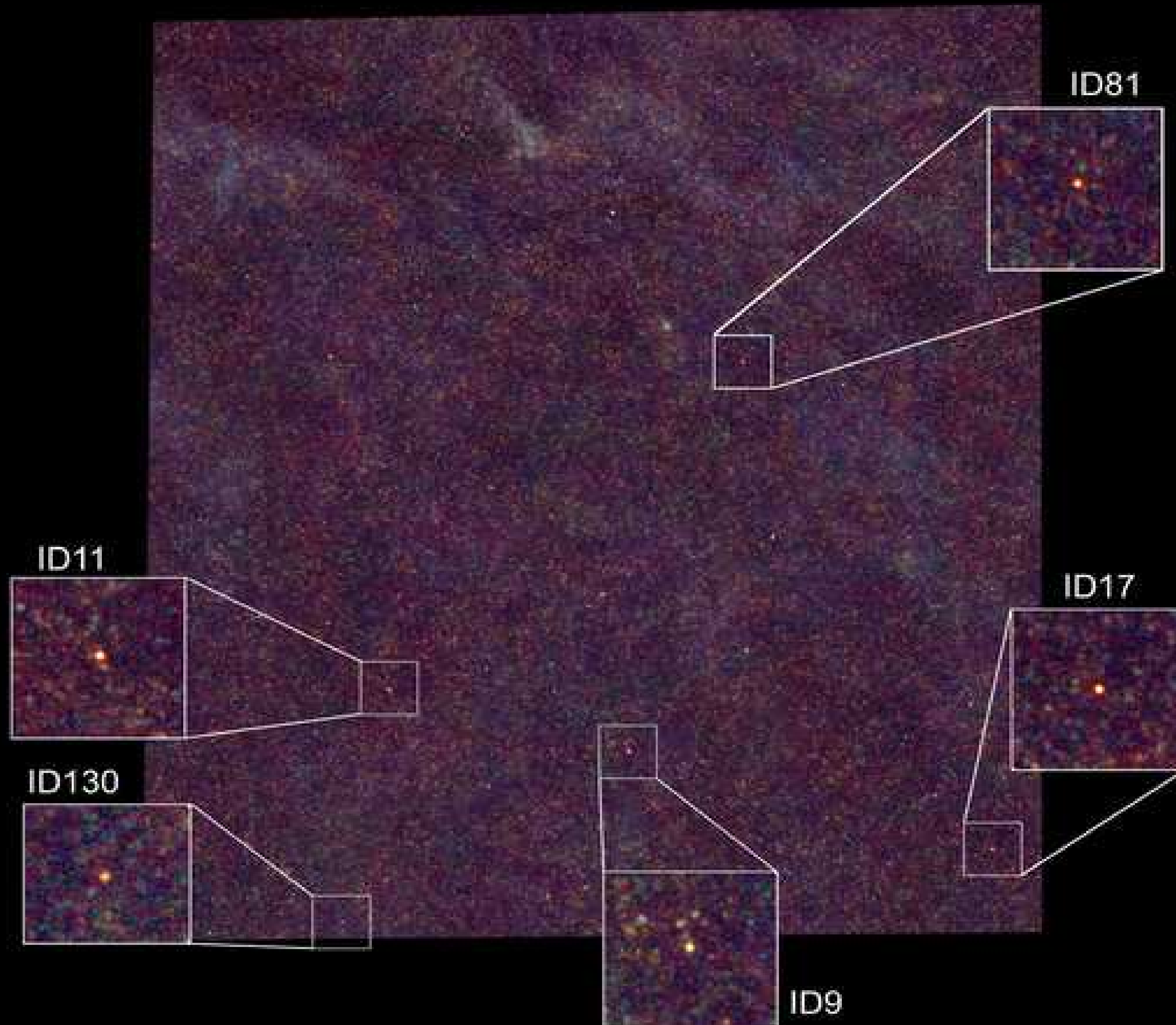
ASPECS Continuum Maps

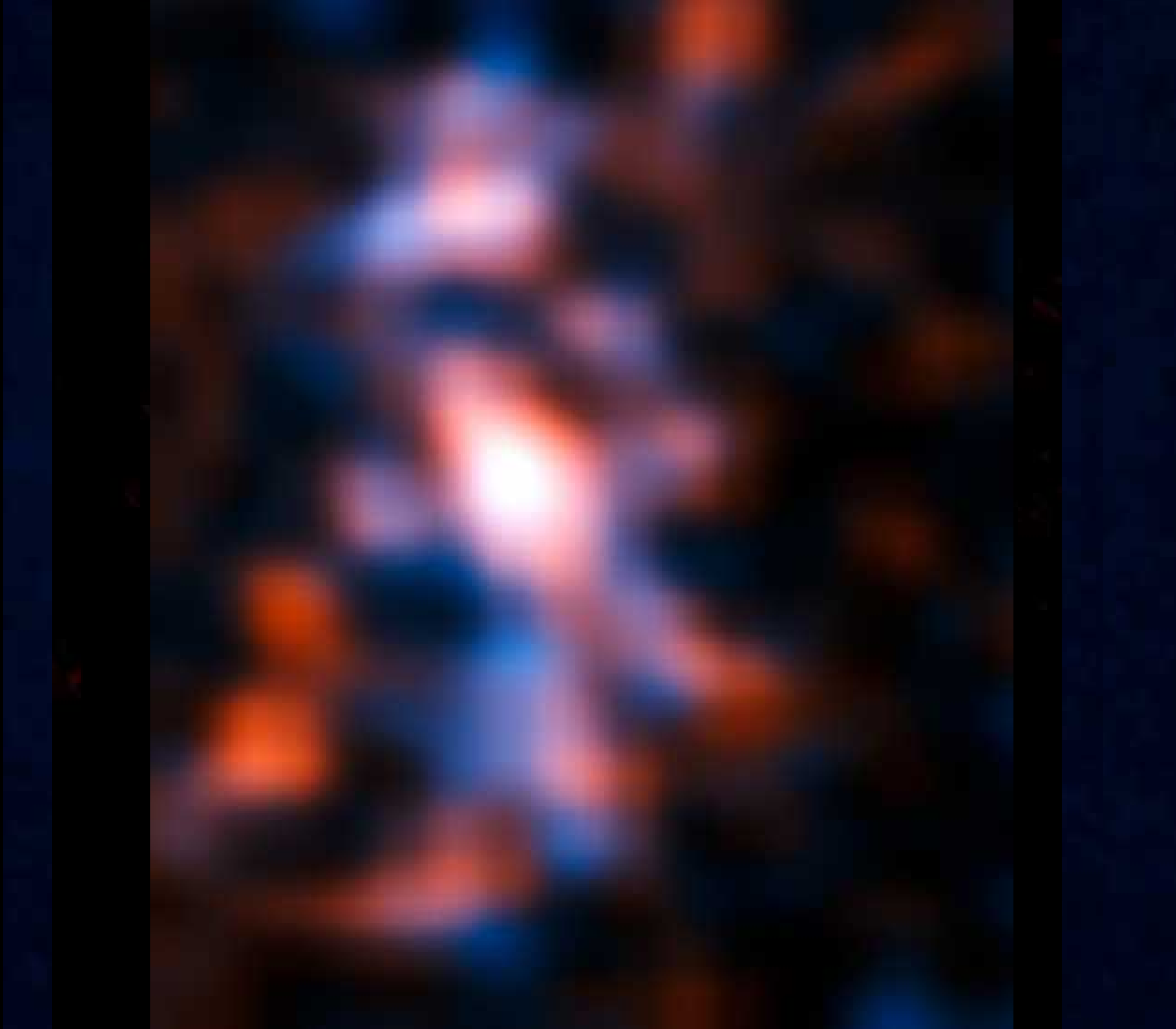




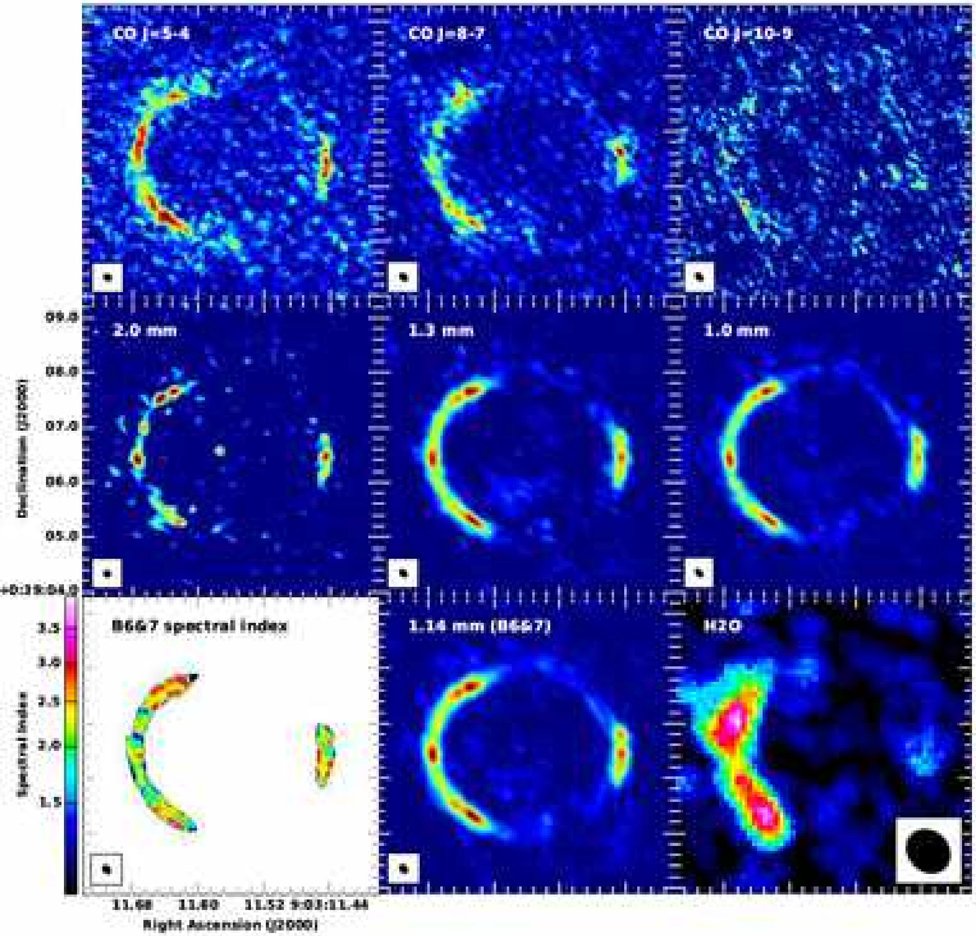
- Nine sources detected at 1.2-mm down to S/N>3.5 (1 Ơ=13 I Jy) within 1 arcmin2 area, with a resolution of 1-2”
- One source detected at 3-mm within 1 arcmin2 area, with a resolution of ~3”

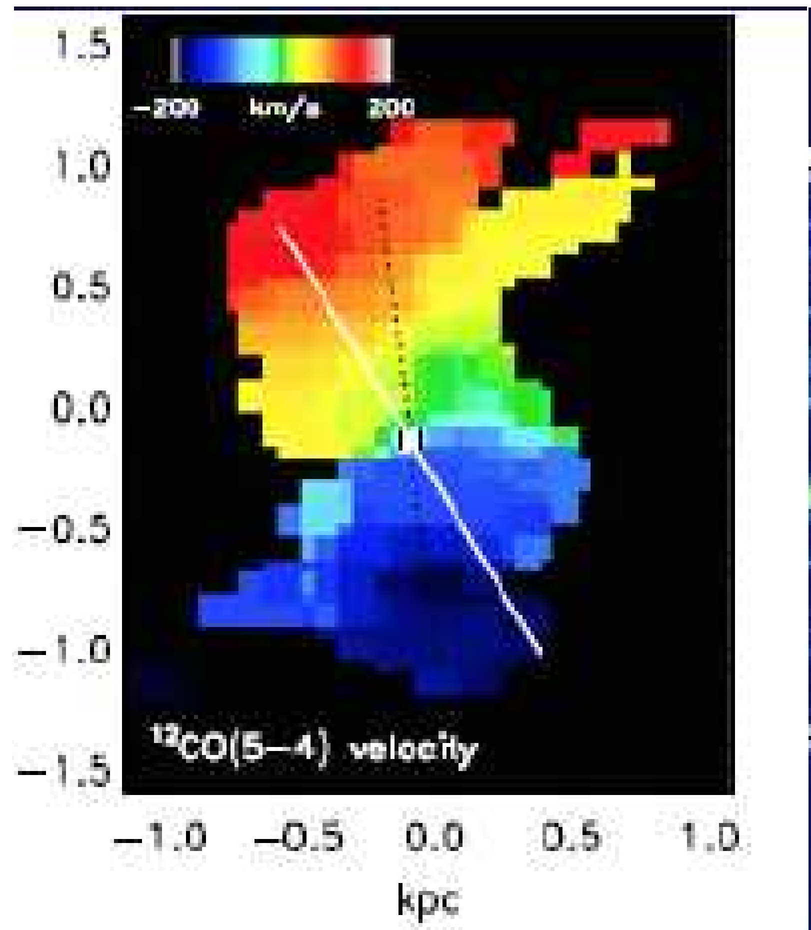
SDP.81 at z = 3.04





1 at z=3.04





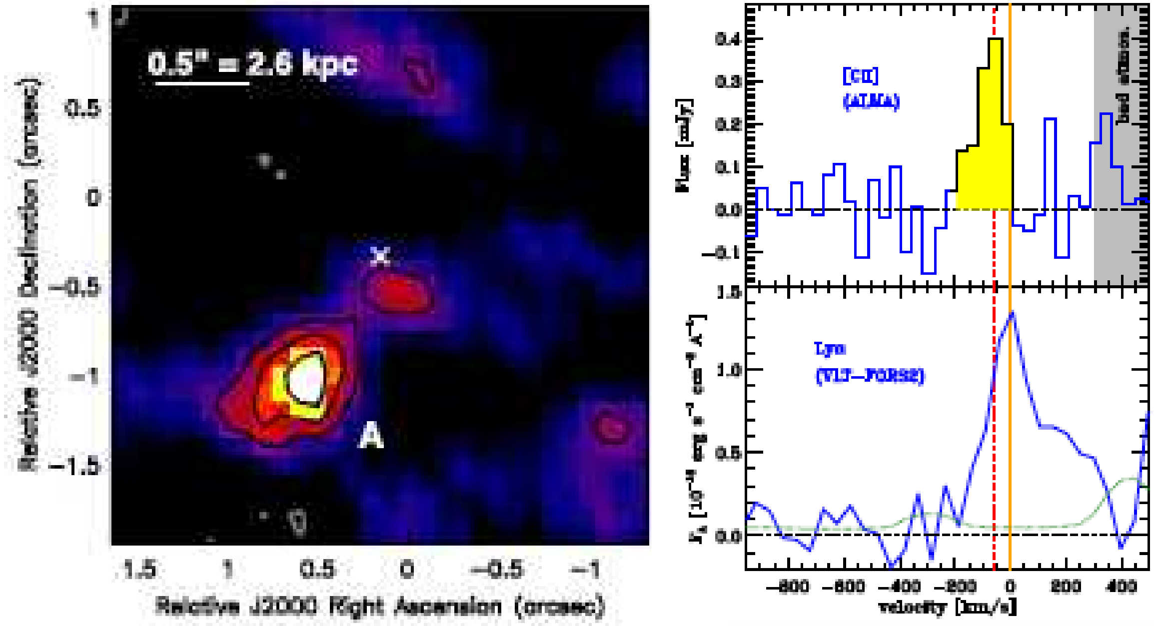
- Clumpy rotating disk; clump/cloud properties on 100-200 pc scale!!
- Toomre instable disk; Cloud/Clump pressures 104 x typical GMC in MW (more like Galactic Center)
- Resolution: 23 mas in continuum and 170 mas in lines

ALMA Partnership, Vlahakis et al. 2015; Dye et al. 2015; Swinbank et al. 2015

The Assembly of 'Normal' Galaxies at z~7

- Deep ALMA observations towards three Lyman Break Galaxies at 6.8<z<7.1
- Star Formation Rates of

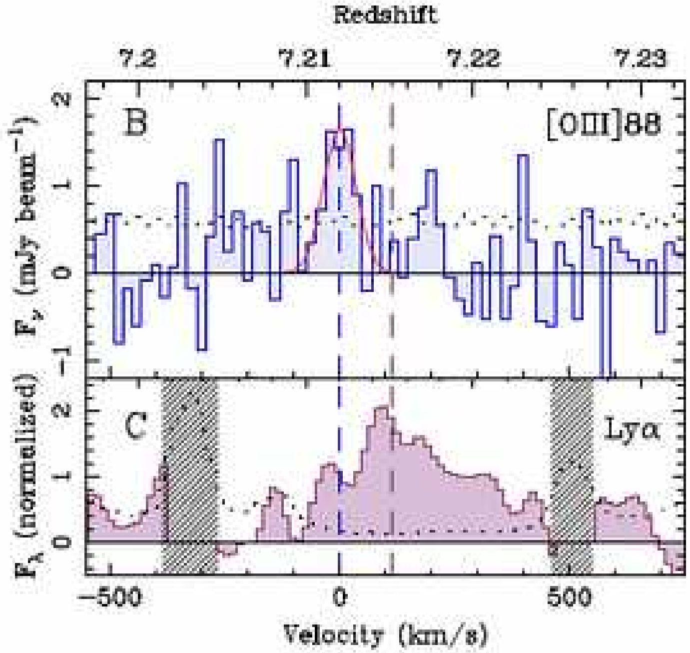
  about 5 -15 M⊙yr-1
- The galaxy at *z*=7.107 is detected in [CII] but offset
- Otherwise neither dust continuum nor [CII] in all three primordial galaxies at position of optical emission
- [CII] arises from external accreting/satellite clumps of neutral gas, in agreement with recent models of galaxy

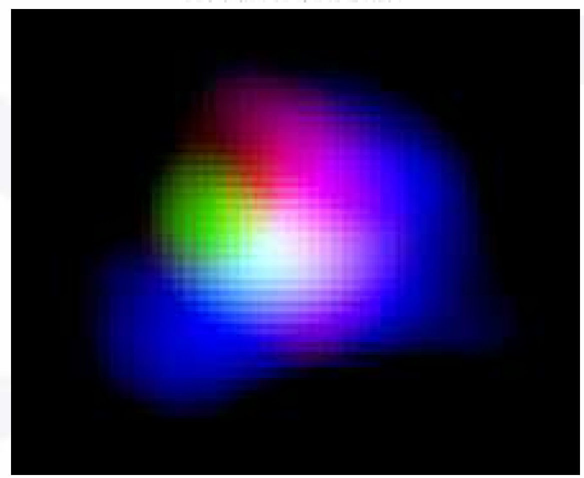


Maiolino et al. (2015) MNRAS 452, 54

Detection of [OIII]Emission Line in a z~7.2 Galaxy

- Detection of [OIII] emission line in a galaxy at z=7.21, SXDF-NB10006-2, that was discovered using the Subaru Telescope
- Neither dust emission nor the [CII] emission line are detected
- The [OIII] emission overlaps with that of Lyα emission (which is more extended due to resonant scattering by neutral hydrogen atoms)
- From SED modeling, the ongoing star formation episode is constrained to 1 million years with a SFR of a few



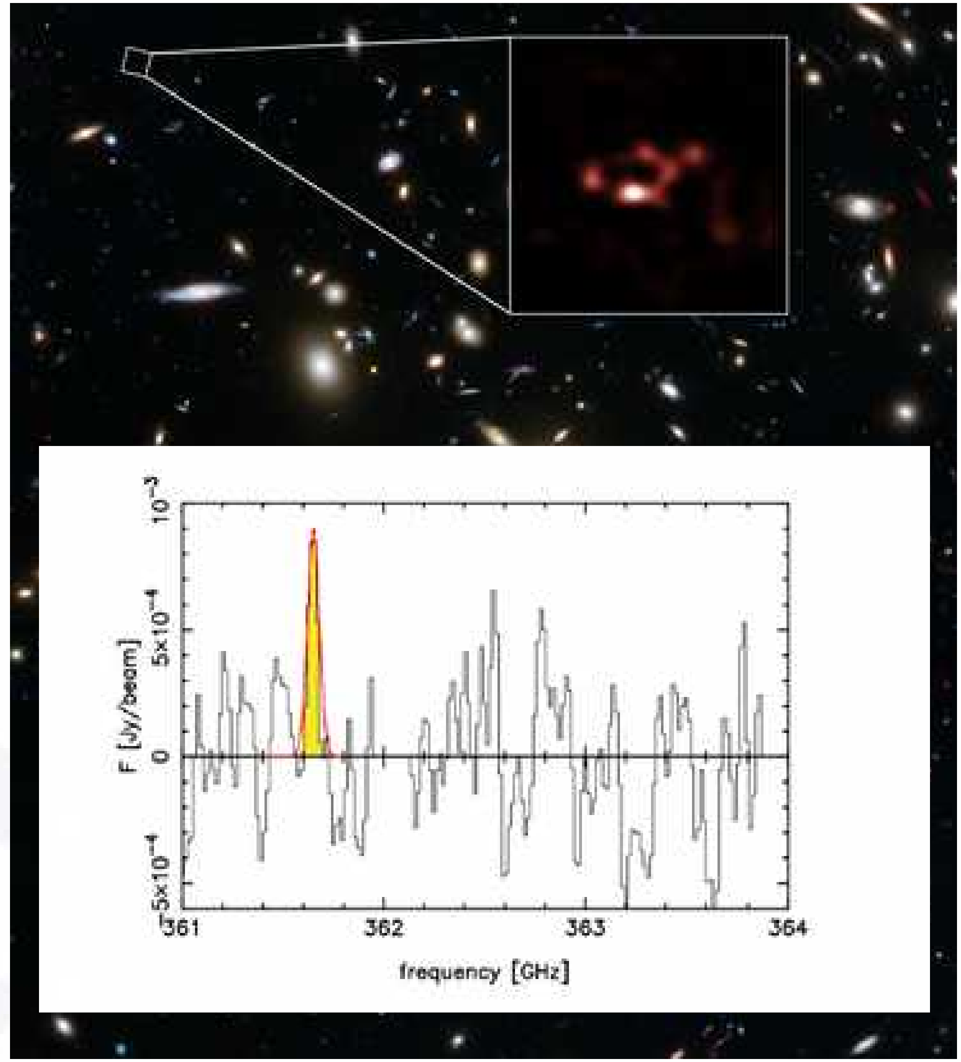


Ionized Hydrogen
UV Light
Ionized Oxygen

Inoue et al. (2016) Science

A z=8.35 Gravitationally Lensed Galaxy

- A2744-YD4, in cluster Abell 2744 (*HST Frontier Field),* detected in Band 7 with ALMA.
- Deep X-SHOOTER spectra detect Lyman α at z=8.38, i.e. 200 Myr after the onset of cosmic reionization
- Confirmed by the presence of a [OIII] 88 μm line
- Magnification of ~2
- M*~2x109 M⊙, SFR~20 M⊙/yr and Mdust~6x106 M⊙



Laporte et al. 2017 ApJL 827, 21

ALMA Highest Science Requirements

* Detect emission from the CO molecule, atomic or ionized carbon towards a galaxy of Milky Way luminosity at a redshift of 3 in less than 24 hours integration.
* The ability to image the gas kinematics in proto-stars and proto-planetary disks around young Sun-like stars at a distance of 150 parsecs, enabling one to study their physical, chemical *and magnetic field structures* and to detected the gaps created by planets undergoing formation in the disks.
* Provide precise imaging at an angular resolution better that 0.1”. Here ‘precise’ means that the ratio of the most intense to the weakest feature in the image can

- Thanks to all ALMA Staff

…. and Thanks for your Attention