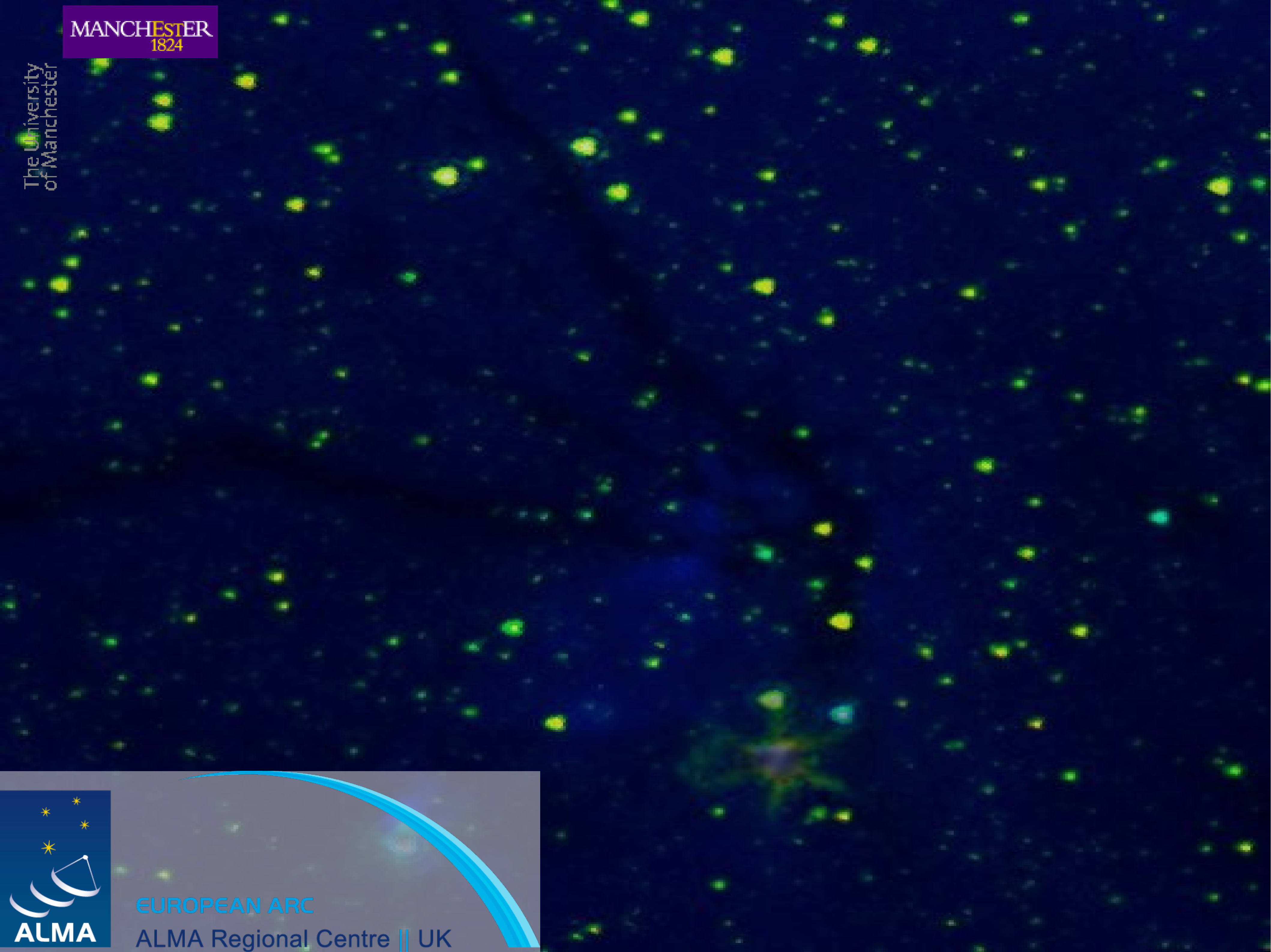

MANCHESTER
1824
The University
of Manchester
ALMA
EUROPEAN ARC
ALMA Regional Centre || UK

The University of Manchester
MANCHESTER 1824

Galactic Star Formation

Peering Into The Dark

Gary Fuller

Jodrell Bank Centre for Astrophysics &
UK ALMA Regional Centre Node
University of Manchester

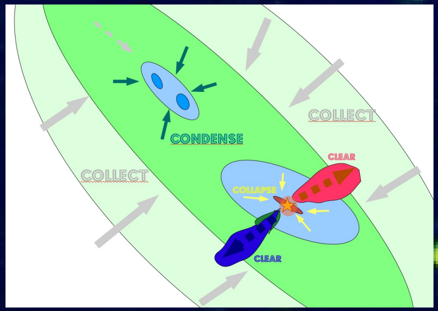
ALMA
EUROPEAN ARC
ALMA Regional Centre || UK

Outline

A quick overview of the star formation phenomena & processes as observed in our galaxy.

- Overview
- ISM
- Low Protostars
- Massive star formation
  - An extreme infrared dark clouds
- ALMA

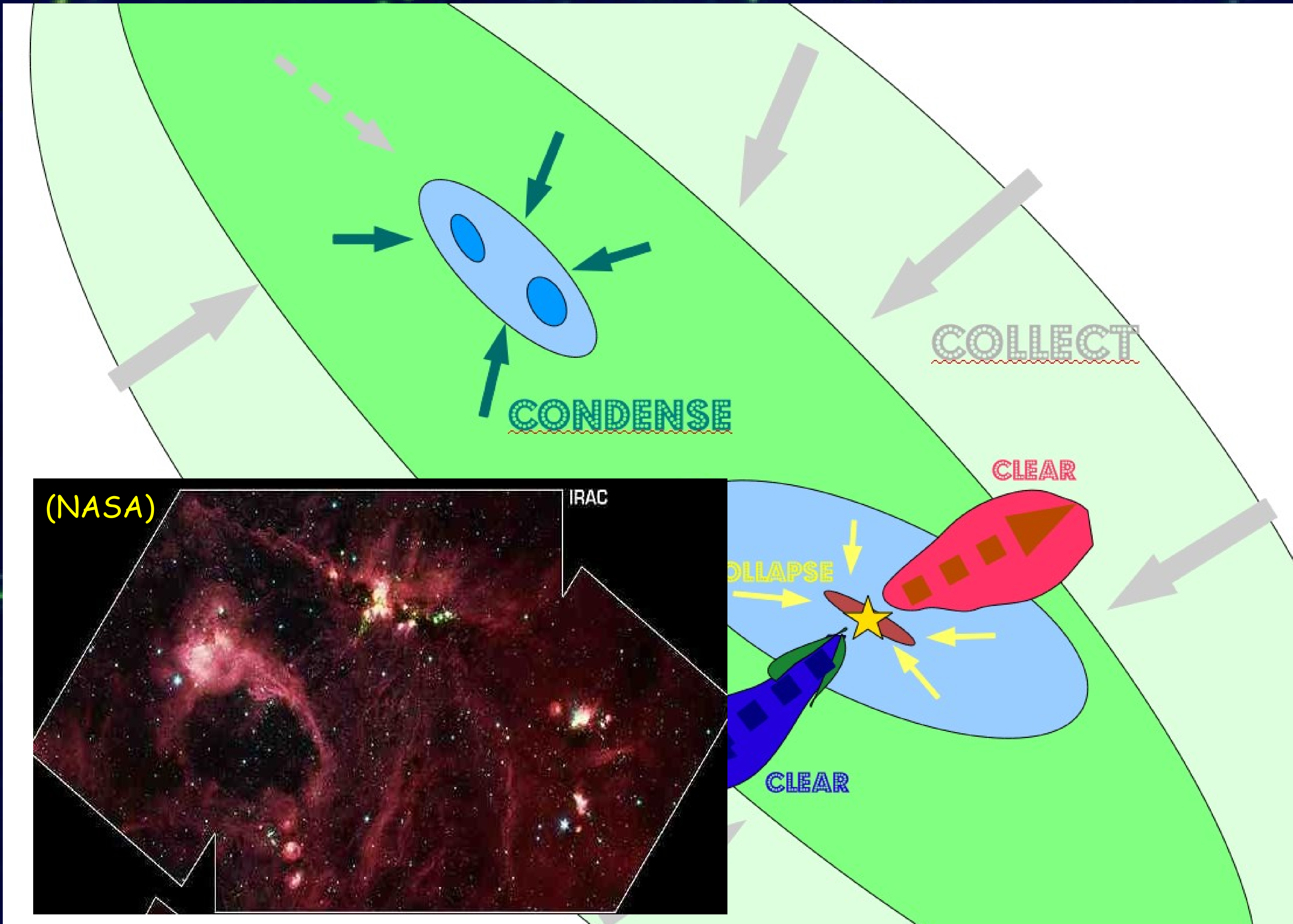
Star Formation: C4D



Fragment

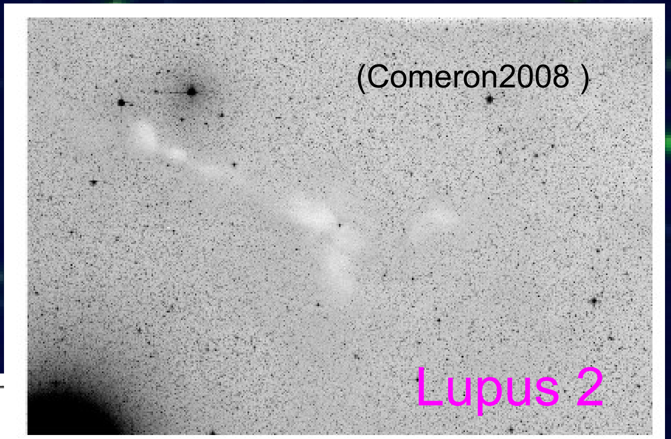
- Collect
  - 10^4 to 10^6 M_o of molecular gas in to a cloud
- Condense
  - Form high density clumps
- Collapse
  - Gravity takes over – central sources form
- Clear
  - Star(s) emerges from natal cocoon
- Disperse
  - (Most) star clusters are unbound

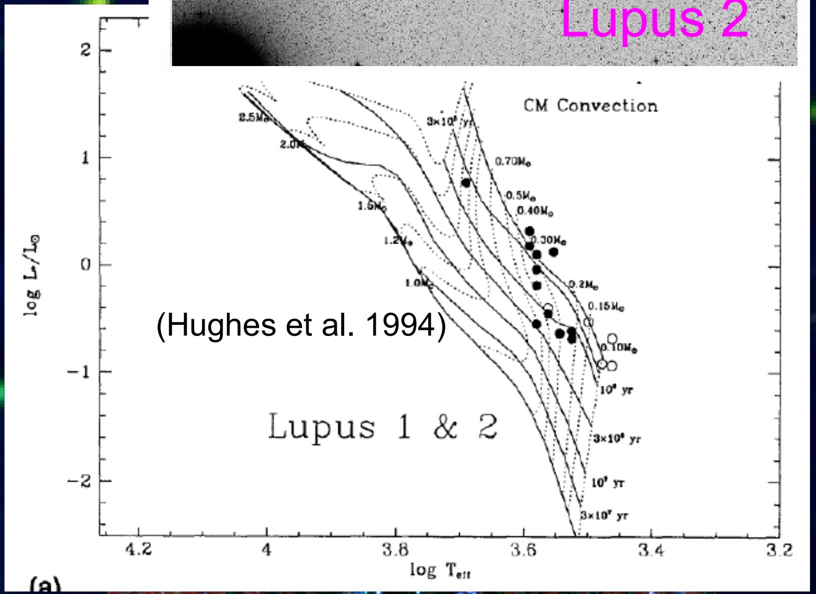
Feedback

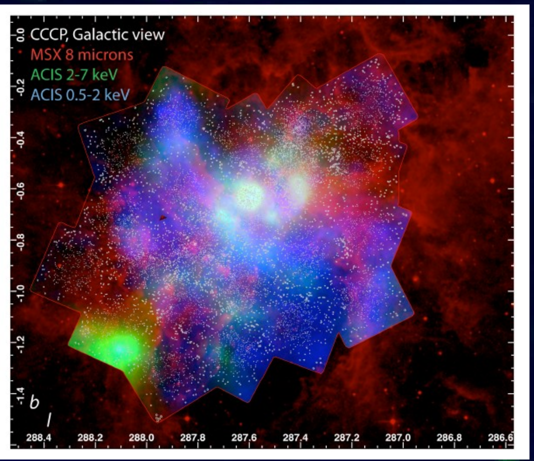

COLLECT
CONDENSE
CLEAR
OLLAPSE
CLEAR
(NASA)
IRAC

Wide Range of Products

- Factor 10^3 in mass
  - 10^{10} in luminosity
- Range of Environments
  - Single stars
  - Binary & multiple stars
  - Clusters
  - Lupus: Stellar masses <0.5 M_o
  - Carina: 70 O/WR stars, M>100 M_o
  - W49: 10^7 L_o
  - Superstar clusters

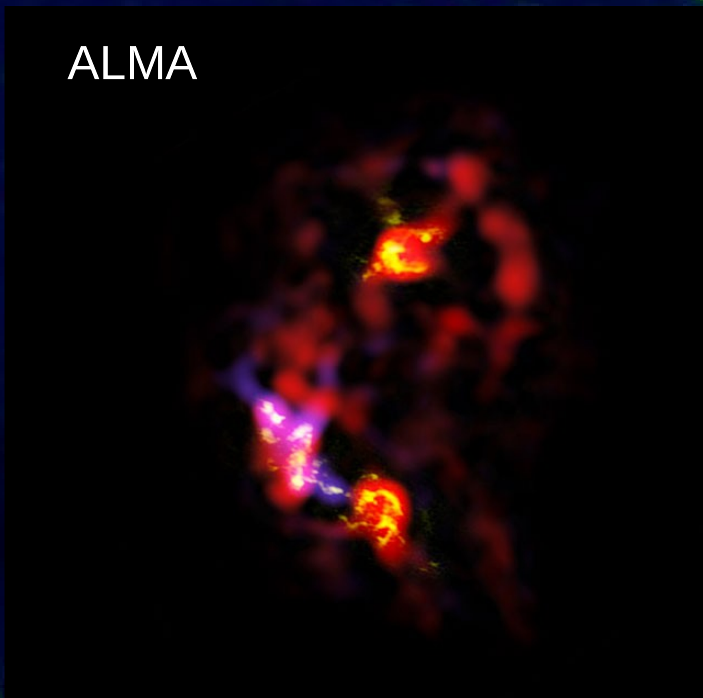




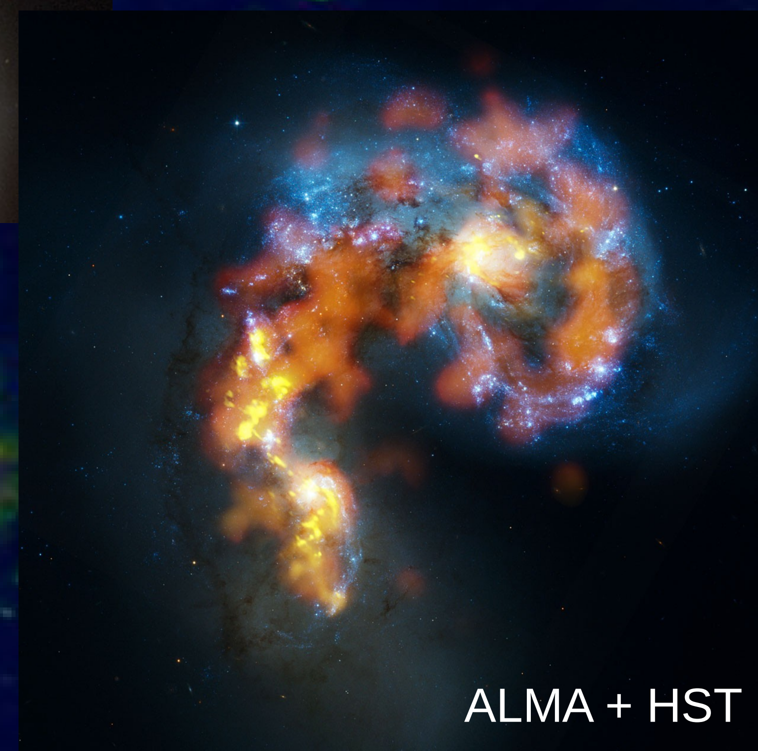


(Townsley et al. 2011)

Antennae Galaxies



(Herrera et al. 2012)

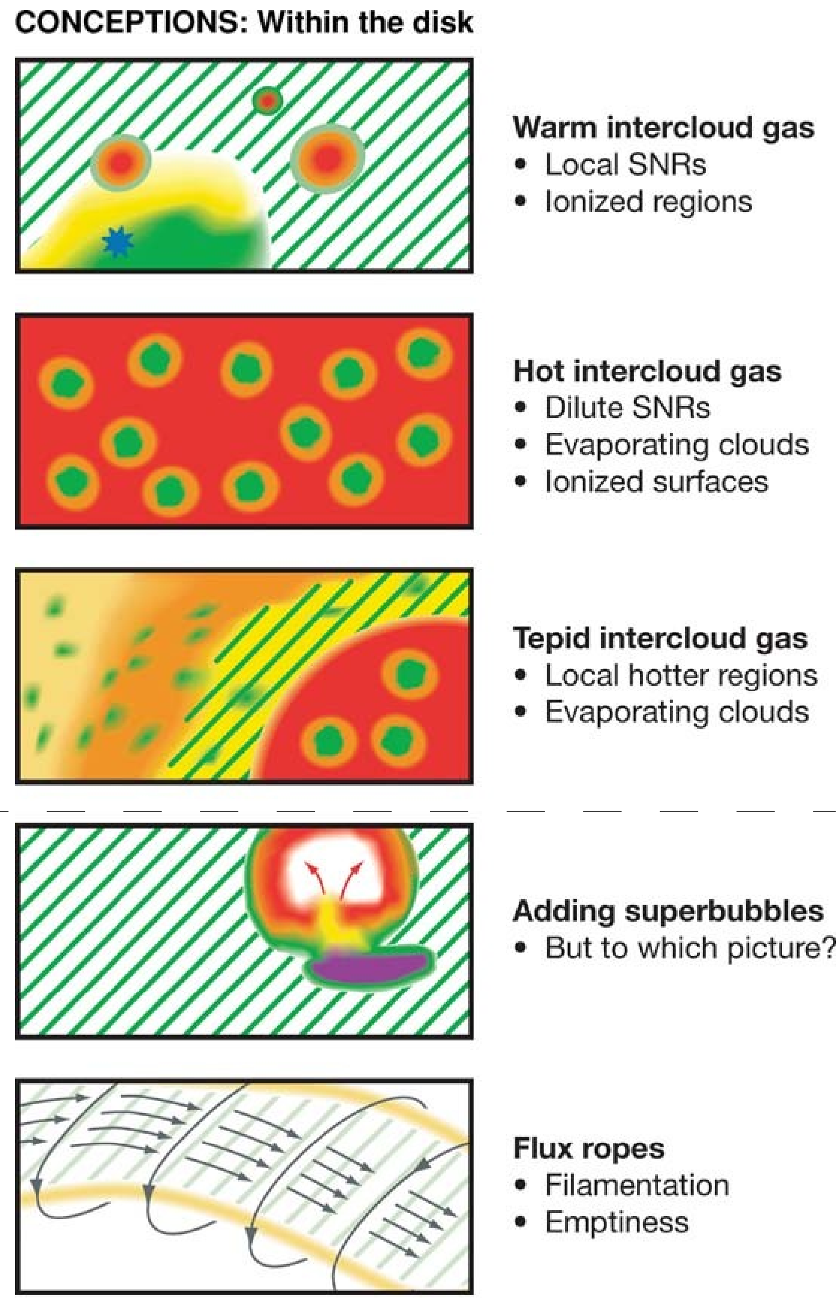


- $10^8 M_o$ Super Giant Molecular complexes
- Superstar clusters of masses 10^4 to $10^6 M_o$
- 5000 O5 stars
- SFR~20 M_o/yr

ISM: A complex multiphase, partially ionized, dusty plasma

- Gas & Dust
  - Hydrogen: ionised (HII), atomic (HI) & molecular (H_2)
  - Dust: Refractory elements (Si, Fe, Mg & C)
    - Silicate, carbonaceous, big/small/very grains. PAHs...
      - Draine 2003, ARAA, Tielens 2008, ARAA
- Heating & Cooling
  - Self shielding (H_2 & CO) & dust shielding (other molecules)
  - PDRs/XDRs/CDRs – interface regions
    - Hollenbach & Tielens 1997, ARAA
- Multiphases of the ISM
  - WIN, CNM, WNM....
    - McKee 1995; Cox 2005, ARAA
- Magnetic fields
  - Crutcher 2012, ARAA
-

HI (Solid – cold, Hatched – warm, Hatched on yellow – diffuse warm)
OVI gas
X-ray gas Molecular clouds

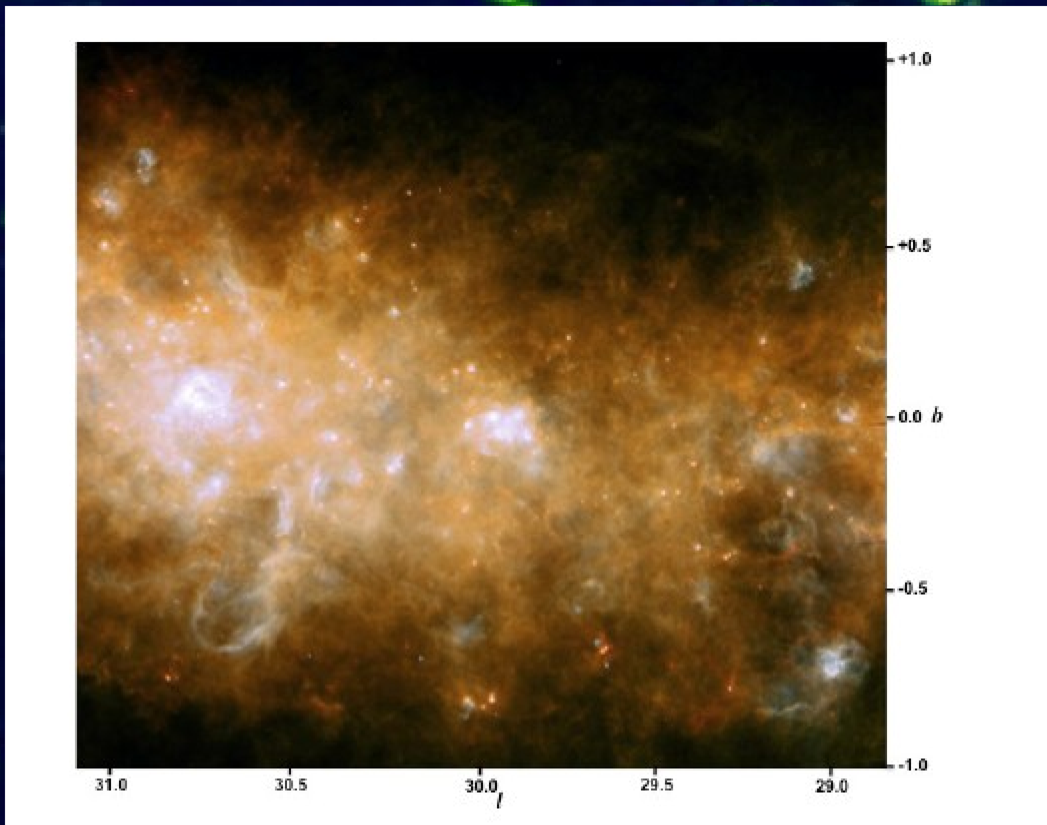


Cox, DP. 2005
Annu. Rev. Astron. Astrophys. 43: 337–85

Tracers

- Dust
  - Absorption & emission
    - Temperature 5 – few 100 K
      - Emission at FIR – mm wavelengths
        - Herschel, SCUBA-2, ALMA
- Gas
  - HI: 21cm spin flip transition
  - HII: free-free (bremstrahlung) radiation, recombination lines (optical to radio). Atomic OIR transitions
  - H_2: No dipole transitions & lowest energy transitions ~500K above ground – shocks but not quiescent molecular gas (5-30 K).
    - Rotational lines of trace molecular species: $[CO/H_2] \sim 10^{-4}$

Dust Emission: Herschel

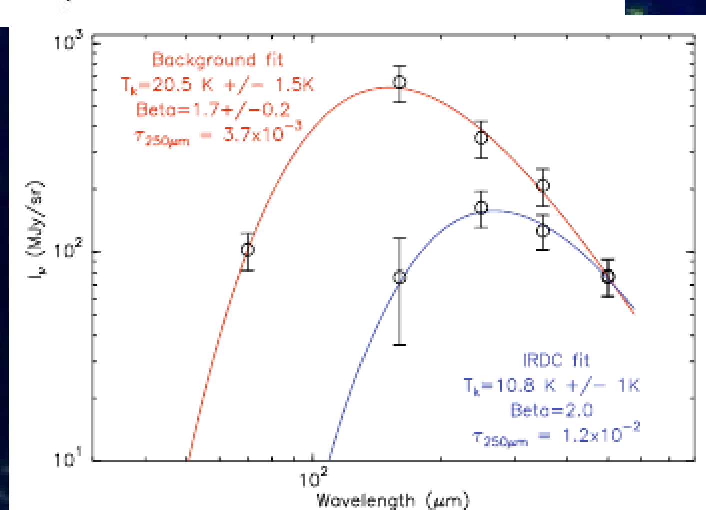


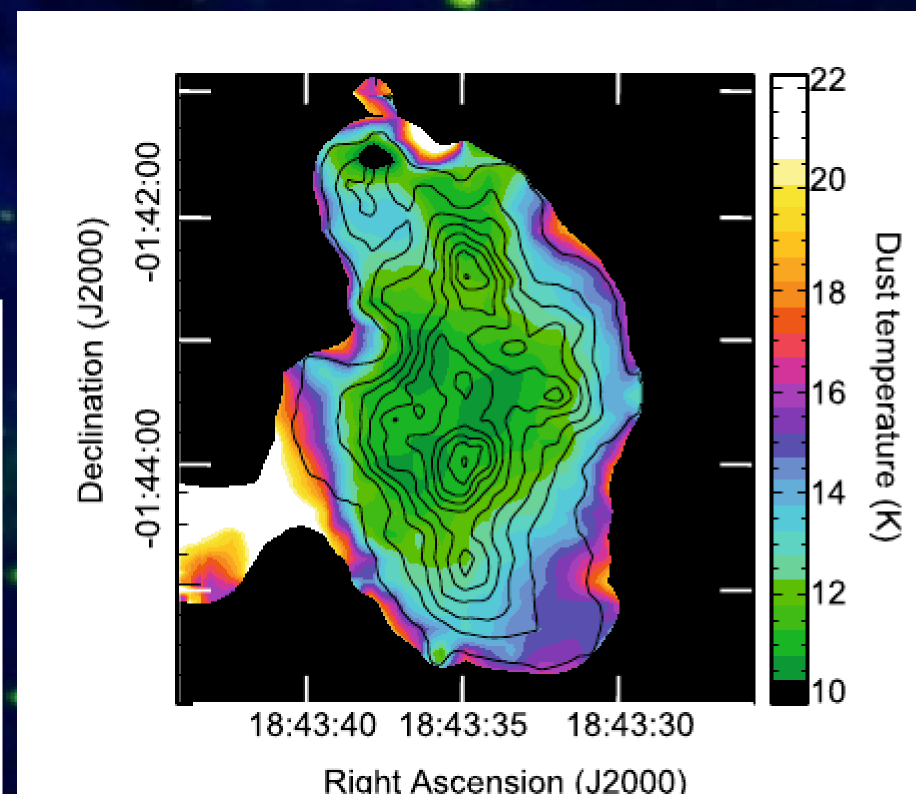
HiGAL Survey: Molinari et al 2010
(70μm, 160μm, 350μm)

(Peretto et al. 2010)

$$I_\nu = B_\nu(T_d)\tau_\nu$$

$$\tau_\nu \propto \nu^\beta$$



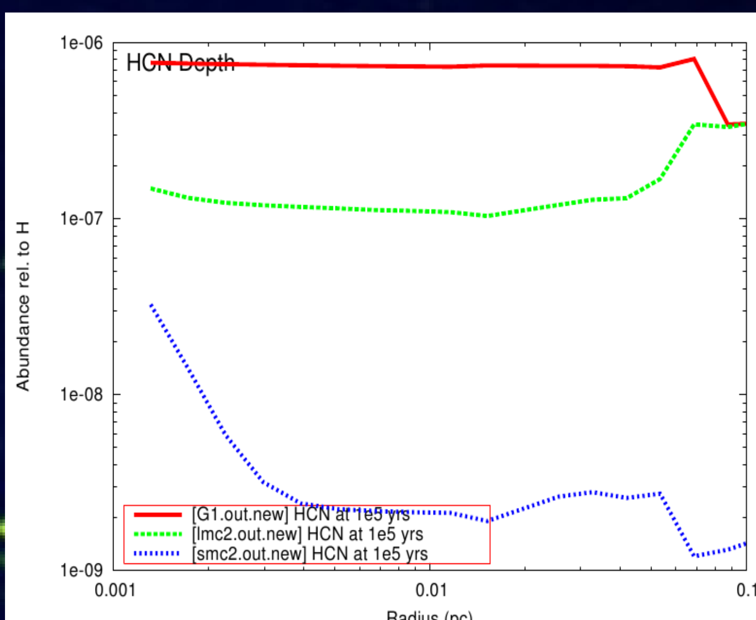


Tracers

- Dust
  - Absorption & emission
    - Temperature 5 – few 100 K
      - Emission at FIR – mm wavelengths
        - Herschel, SCUBA-2, ALMA
- Gas
  - HI: 21cm spin flip transition
  - HII: free-free (bremstrahlung) radiation, recombination lines (optical to radio). Atomic OIR transitions
  - H_2: No dipole transitions & lowest energy transitions ~500K above ground – shocks but not quiescent molecular gas (5-30 K).
    - Rotational lines of trace molecular species: $[CO/H_2]\sim10^{-4}$

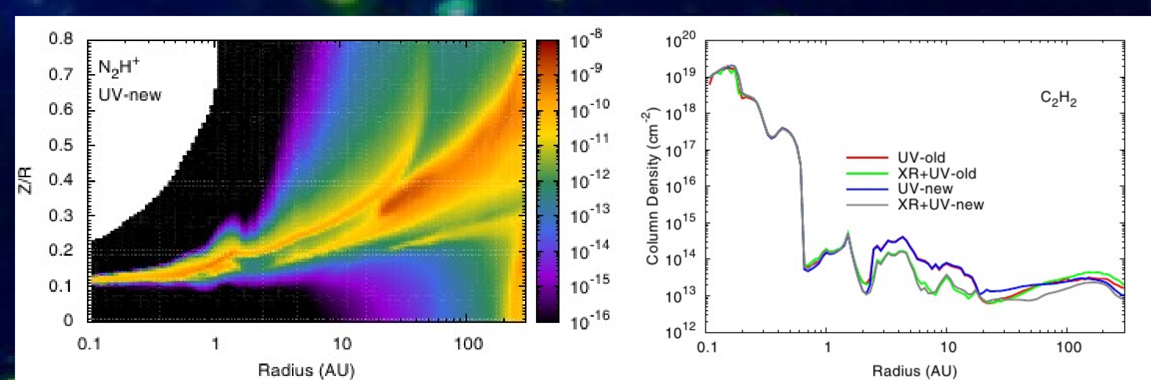
Molecular Astrophysics & Astrochemistry

- ~170 detected species, >50 in external galaxies
  - CO, AlF, HCl^+, H_3^+, CN-, C_6H-, SiC_2, C_{60}, glycolaldehyde ($C_2H_4O_2$- Jorgensen et al 2012)
  - http://www.astro.uni-koeln.de/cdms/molecules
- Chemical models: atomic compositions, physical conditions, reaction rates (gas & grains) → molecular abundances → line emission
  - Past and current state of the gas
    - Bayet et al 2008, 2009, 2010
    - Herbst & van Dishoeck 2009, ARAA, van Dishoeck & Blake 1998, ARAA
- Masers:kinematics at very high resolution. Evolution of massive protostars ?



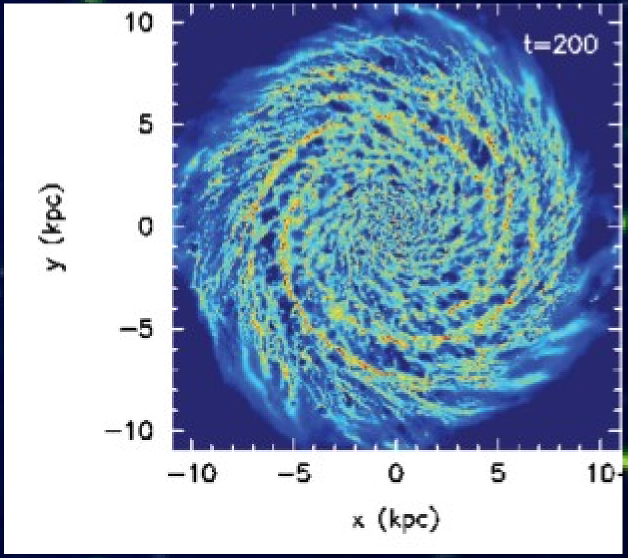
(Kunawicz et al. 2010)

(Walsh et al. 2012)

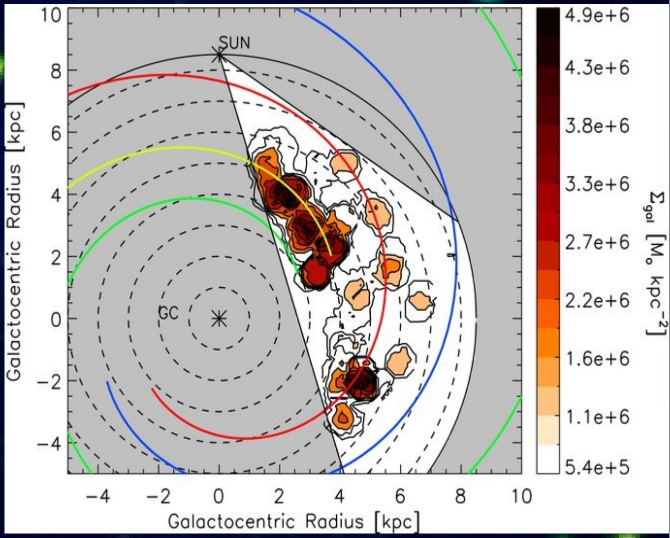


Structure

(Dobbs et al. 2012)

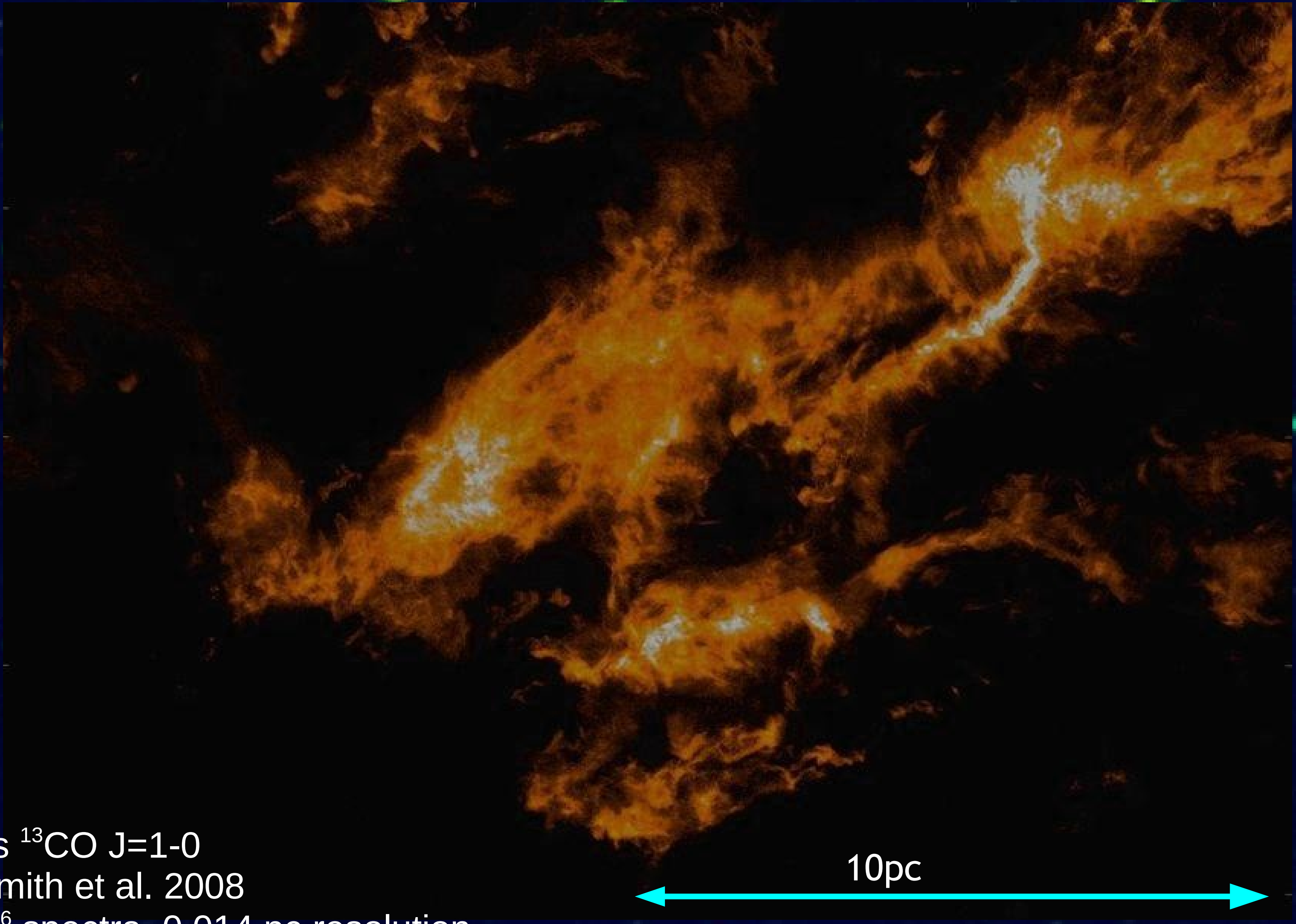


- Clouds – Giant molecular clouds
  - 10's pc in size, 10^2 cm^{-3}, 5-10K, 10^3-10^6 M_o
  - ~10^9 M_o in Milky Way
  - CO
- Clumps
  - Dense substructure within clouds – capable of forming multiple stars (a \`cluster')
  - >10^3 cm^{-3}, ~1pc, 10-1000 M_o
  - ~10% of mass in GMC
- Cores
  - Precursors to ~individual stars
  - Nearby, low mass SF regions: 0.1pc, 10^4 cm^{-3}, few M_o
  - High mass SF regions: smaller, denser
- Linewidths dv> thermal width (σ^2=kT/m)
  - turbulence – dominant pressure
  - Smaller in smaller/denser regions
  - Larson law (Larson 1981)



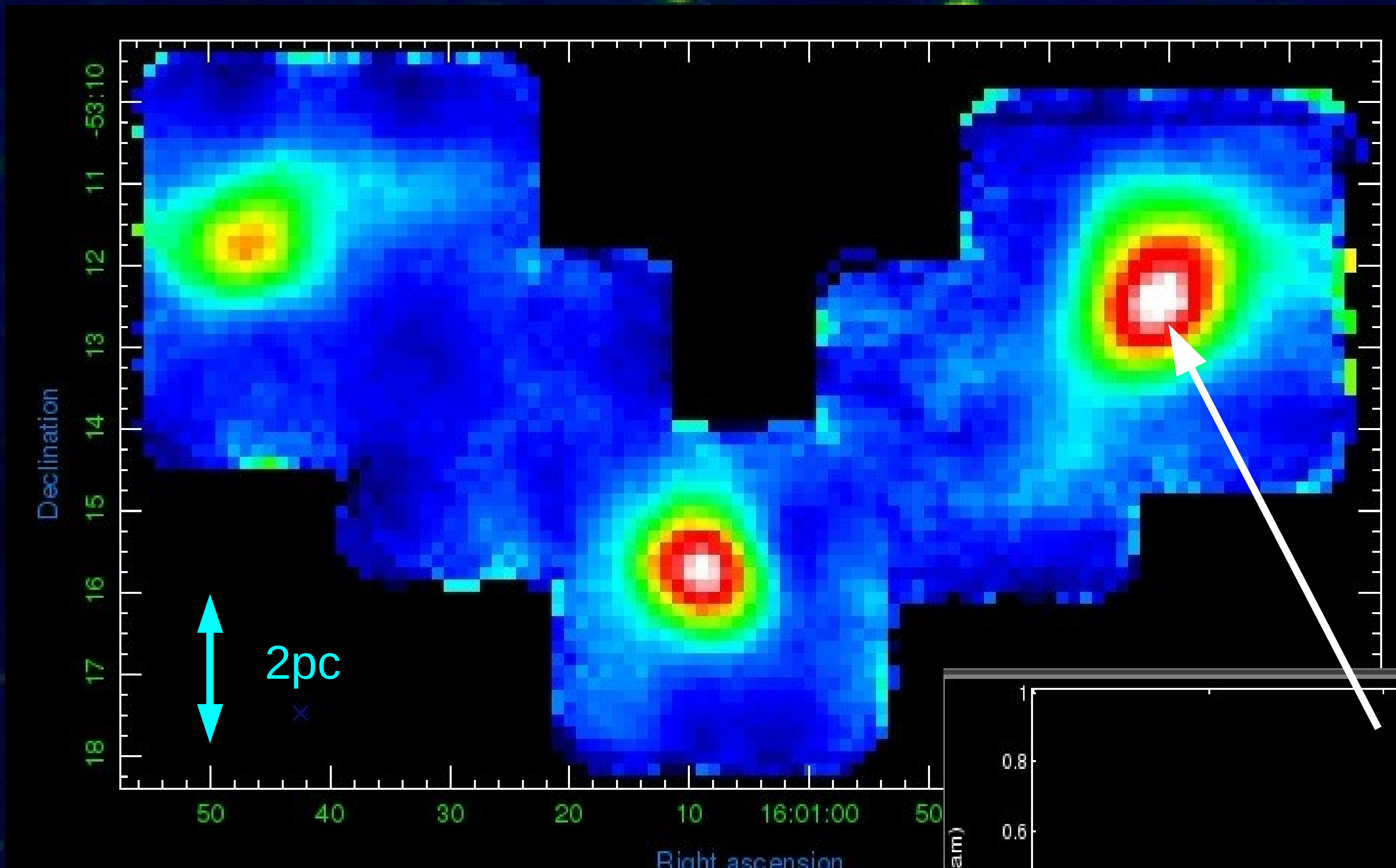
(Roman-Duval et al 2010)

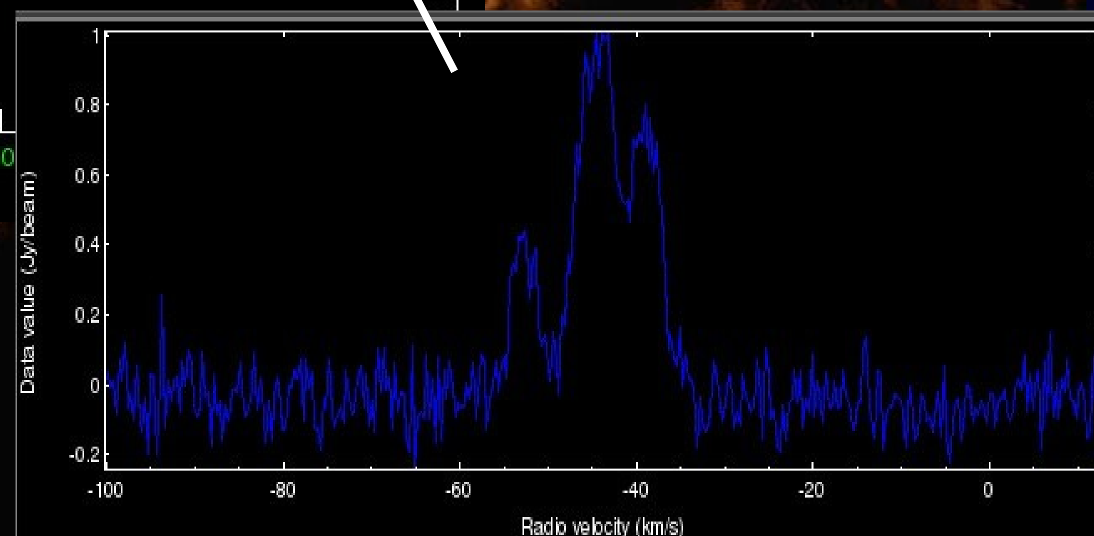
Detail...



Taurus ^{13}CO J=1-0
Goldsmith et al. 2008
~3×10^6 spectra, 0.014 pc resolution

Denser Gas





N_2H^+ J=1-0 93 GHz
Mopra
One pixel but 8GHz IF BW (2012)
- HNC, HCO^+, HCN, SiO

Evolution/Models

- Constraints
  - Galactic star formation rate: 1 – few M_o/yr (Chomink& Povich 2011)
    - ~10^9 M_o in Galaxy collapsing in a free-fall time ~30 M_o/yr
      - Clouds not in free-fall collapse
  - Cloud lifetimes/ages: 1 to 10 free-fall times (Elmegreen 2007)
  - Efficiency: few % of GMC converted into stars
  - Support?
    - B fields
    - Turbulence
      - Vazquez-Semadeni 2012
  - Feedback
  - IMF
    - Bastian et al. 2010, ARAA
      Kennicut & Evans 2012, ARAA

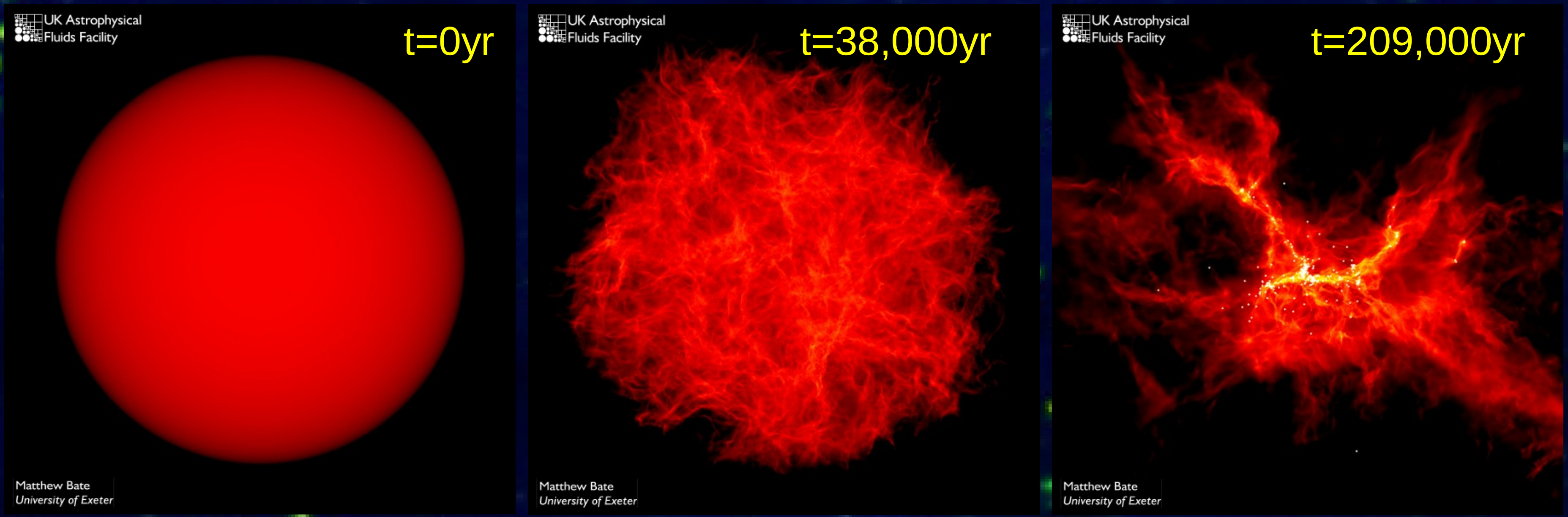
(Semi-)Analytic Models

- Singular Isothermal Sphere (SIS)
  - Shu 1977; Shu et al 1987 ARAA
  - Self similar collapse of $1/r^2$ isothermal density profile
  - Infall starts at centre & travels outwards
  - Constant mass infall rate
- Extending SIS
  - Disks, Winds -
  - Massive star formation – Myers & Fuller 1995, McKee & Tan 2003

Numerical Models

- Range of numerical models
  - SPH vs. grid codes
  - Nature of turbulence
  - B fields
  - Initial conditions
  - Heating & cooling
  - Feedback
  - Groups:
    - Klessen, MacLow, Bate, Hennebelle, Bonnell, Glover, ….

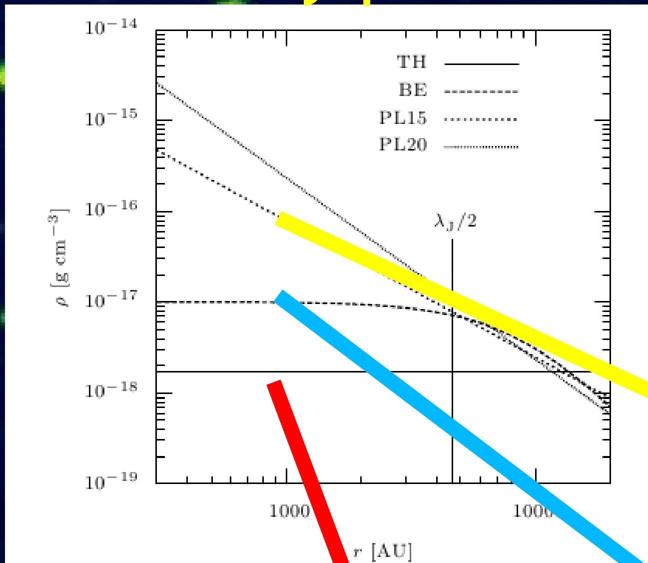
Model for the collapse of a cluster forming clump



1pc (1' at 4kpc), $500M_o$ (Model by M. Bate)

- Highly structured
- Fast collapse

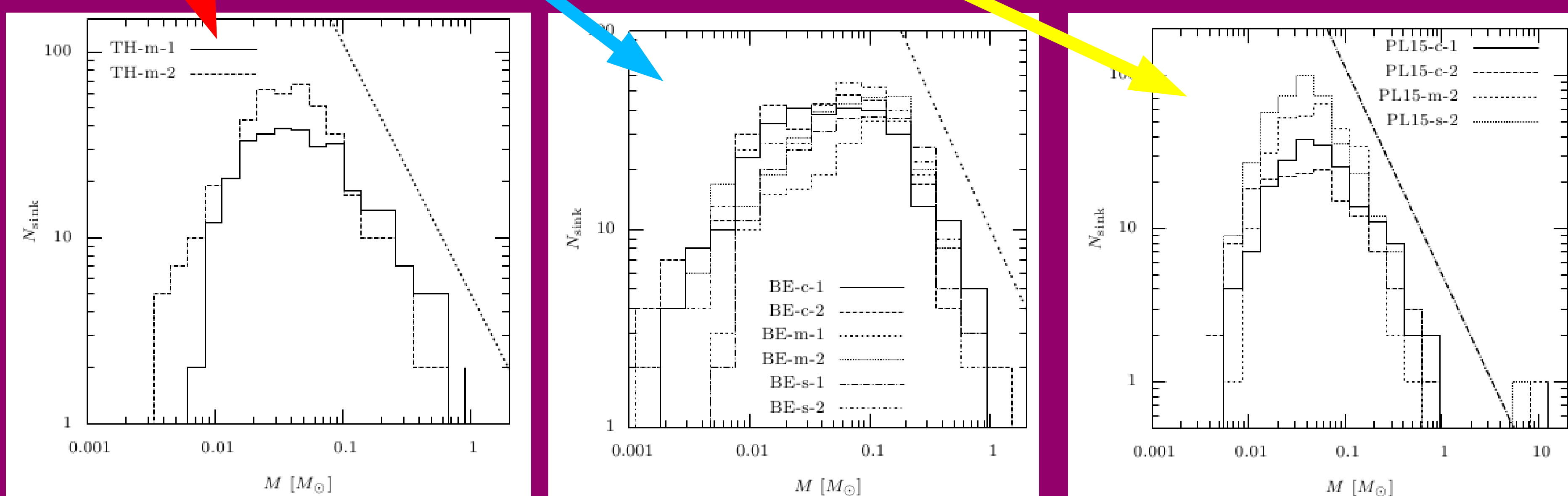
Density profiles



Effect of Density Profile

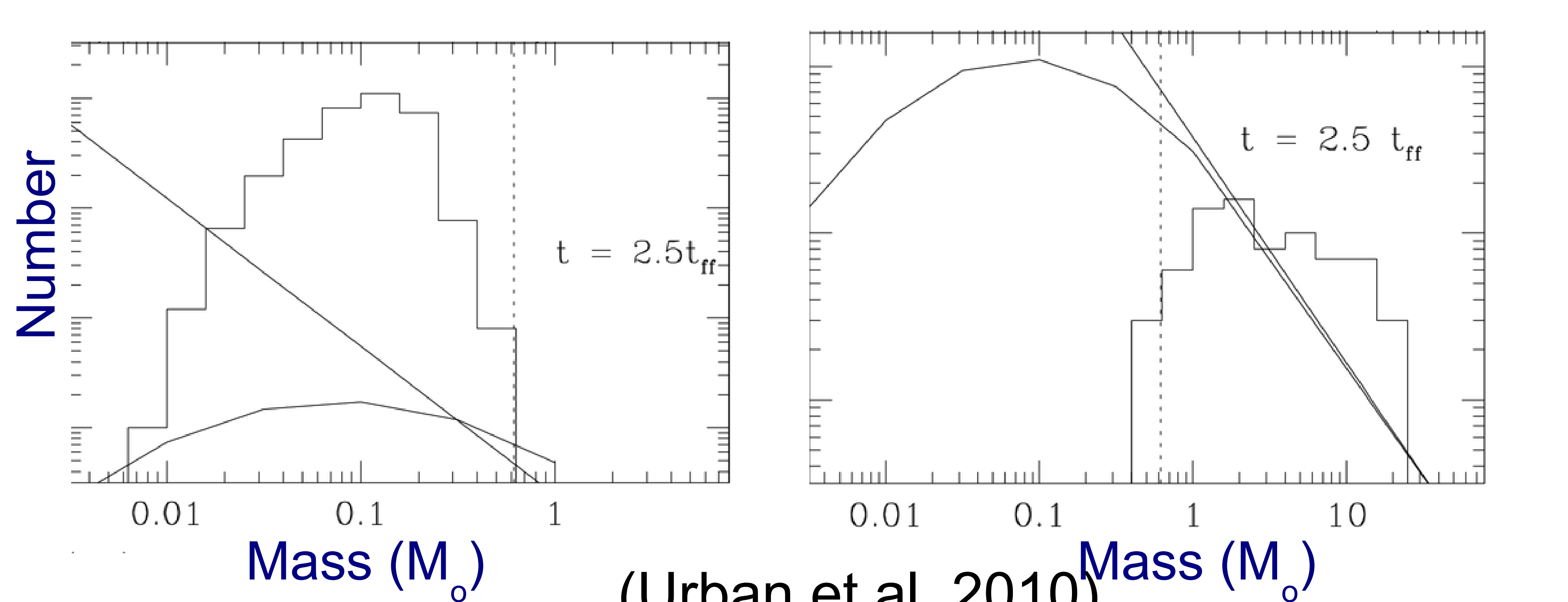
- Collapse of 100 M_0 cloud
  - Isothermal (T=20 K)

Only centrally condensed clouds form massive stars



(Girichidis et al. 2011)

Impact Of Temperature Profile

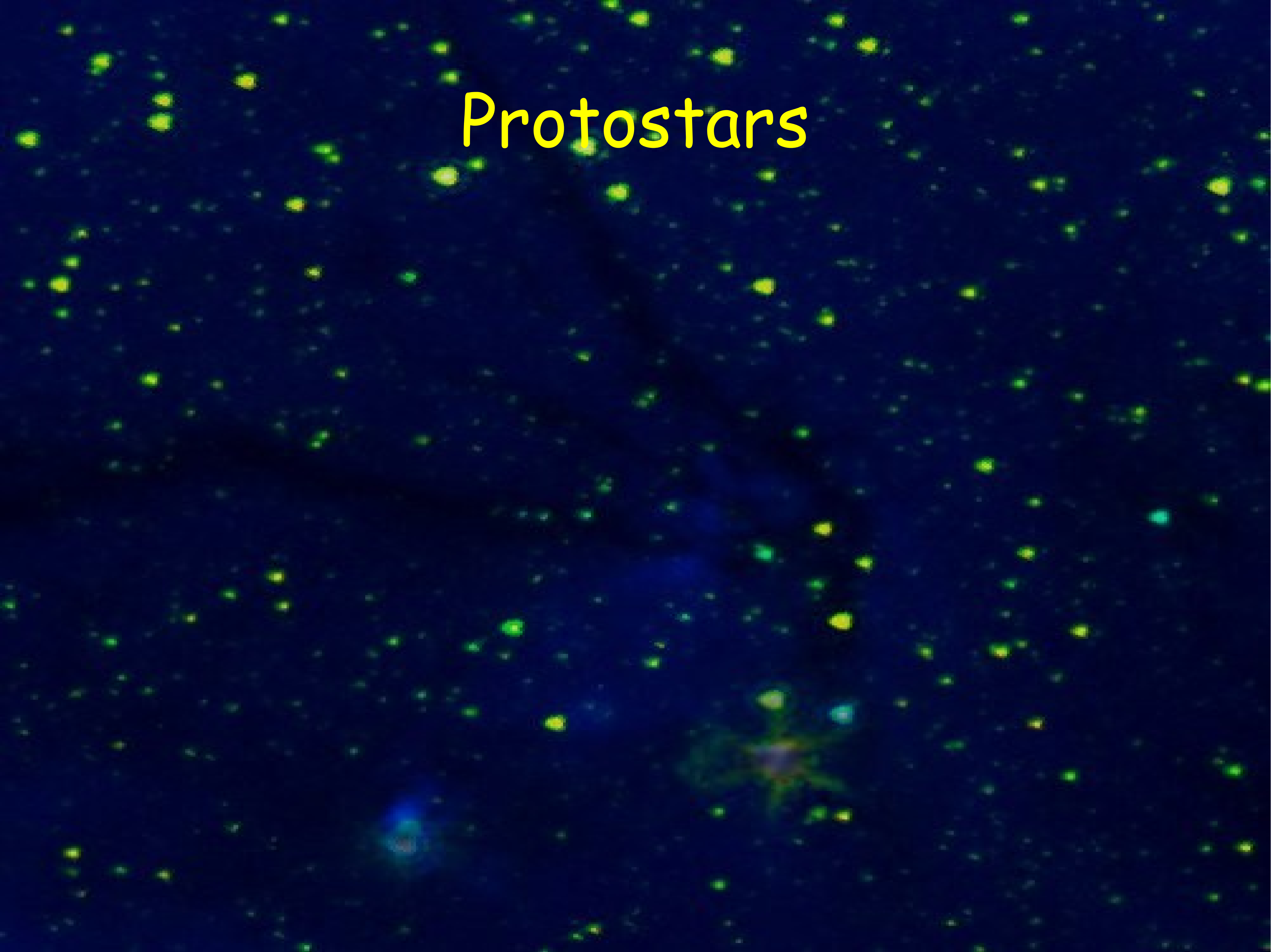


(Urban et al. 2010)

- Heating suppresses fragmentation

  (Urban et al. 2010, Krumholz et al.2007, 2010, Offner et al. 2009, Bate 2009)

Protostars



Timescales

- Stellar Evolution timescales
  - MS lifetimes:
  -

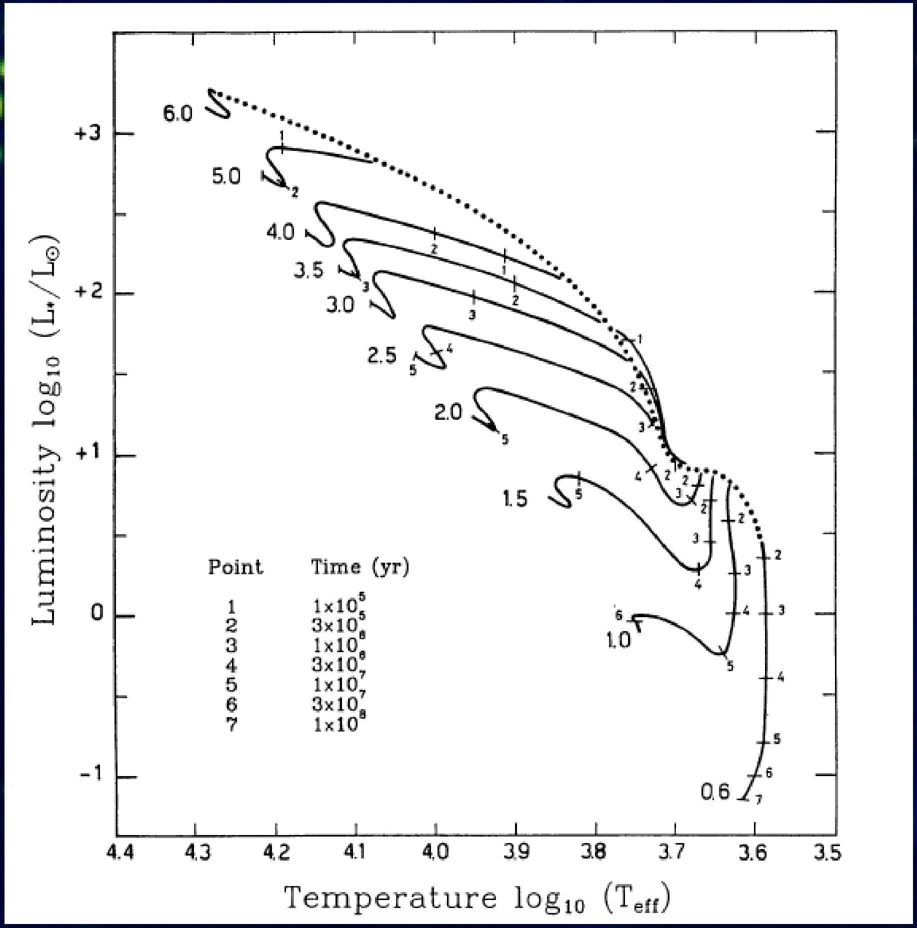
Mass (M_o)	Lifetime (yr)	Luminosity (L_o)
1	10^{10}	1
10	25×10^{6}	6×10^{3}
60	3.5×10^{6}	10^{6}

- Gas timescales
  - Free fall
  - Kelvin-Helmholtz
  - Ambipolar diffusion
  - Chemical

$$\tau_{\rm ff} = \left(\frac{3\pi}{32 G\rho}\right)^{1/2} = \frac{3.5\times 10^{5}}{n(10^{4}{\rm cm}^{-3})}{\rm yr}$$

$$\tau_{\rm KH} = \frac{GM_*^2}{R_* L_*} = 3\times 10^{7}\frac{M_*(M_\odot)^2}{R_*(R_\odot)L_*(L_\odot)}{\rm yr}$$

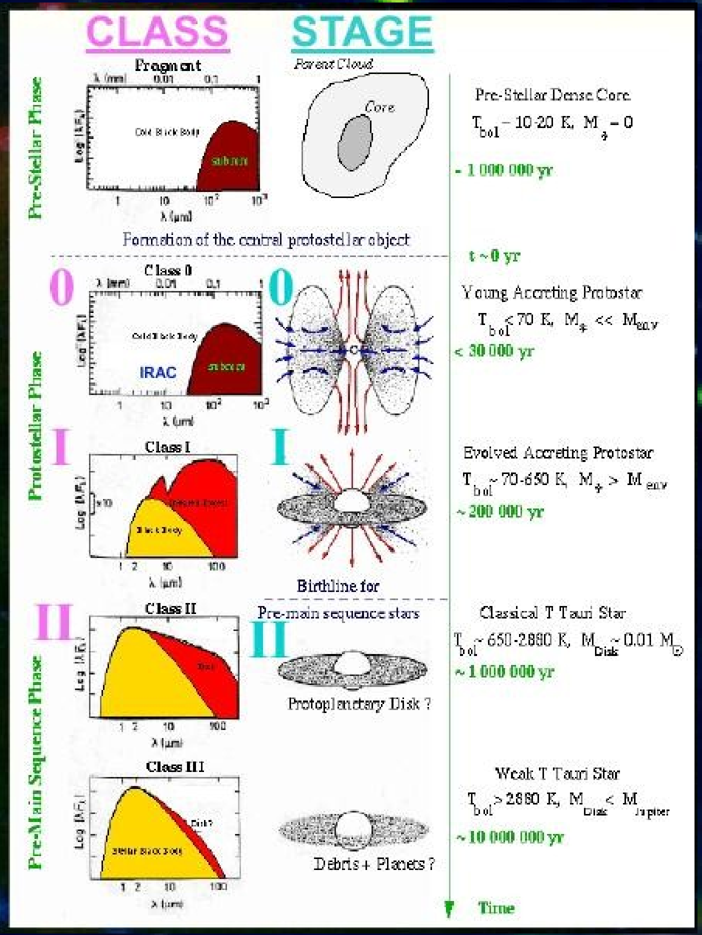
PMS Tracks



(Palla & Stahler 1993)

- Low mass: Tognelli et al. 2011
- High mass: Hosokawa et al. 2009, 2010

Low Mass Protostars

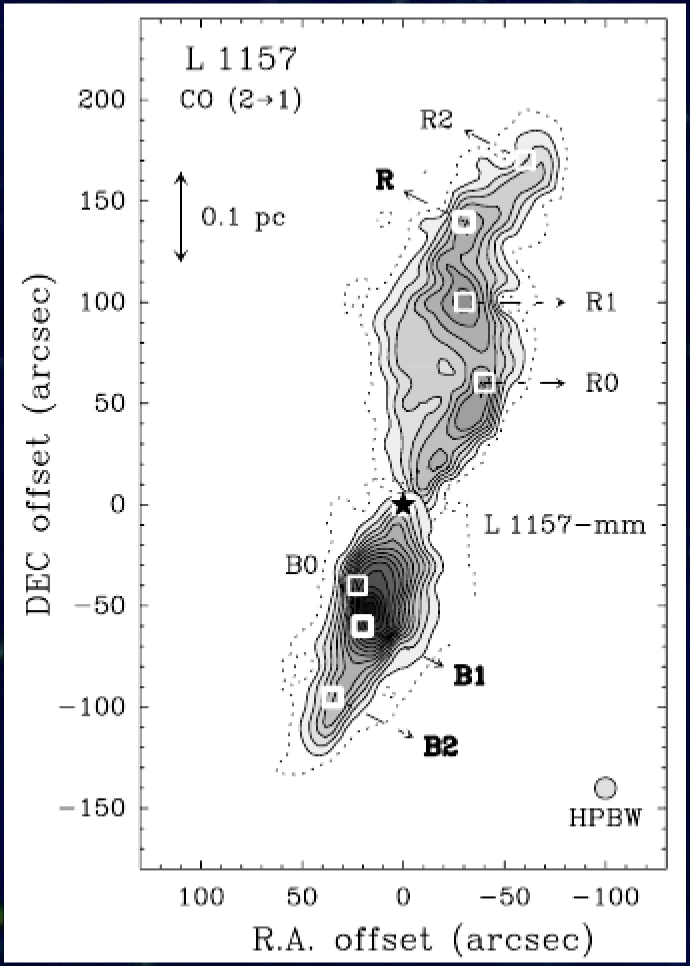


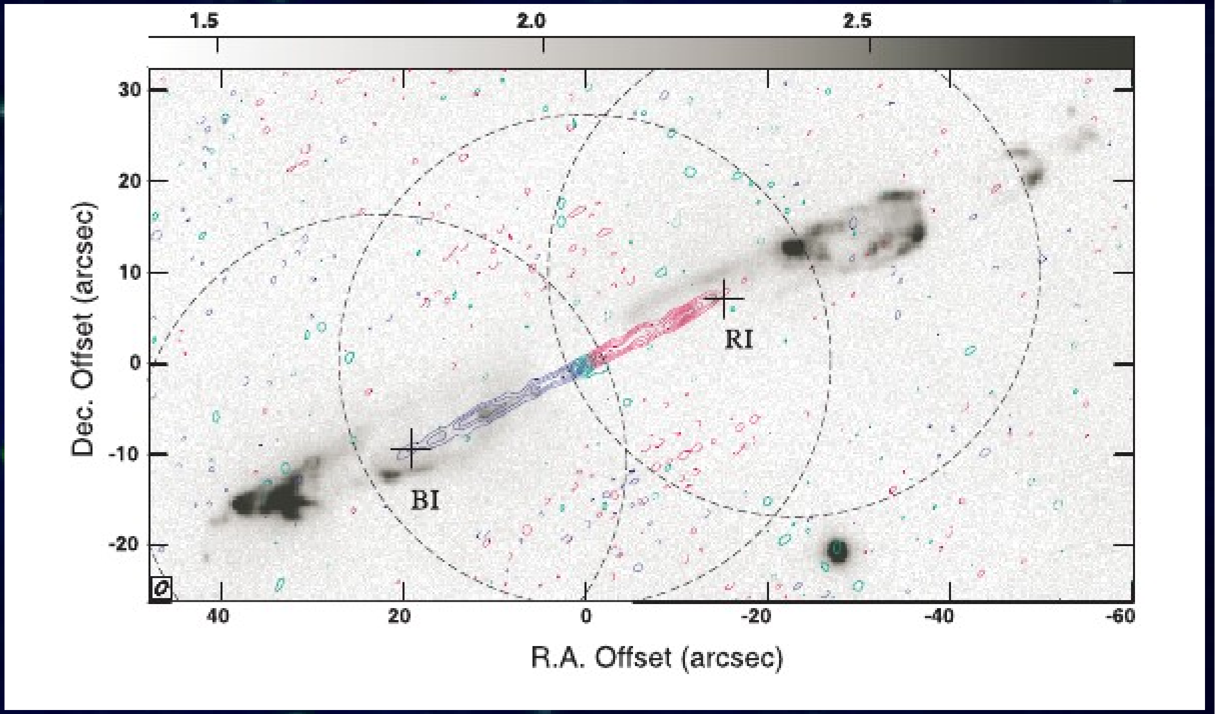
(Lada; Andre et al. 1993; Enoch)

Outflows

- Shang et al. 2007, Protostars & Planets V;
- Pudritz et al. 2007, PPV

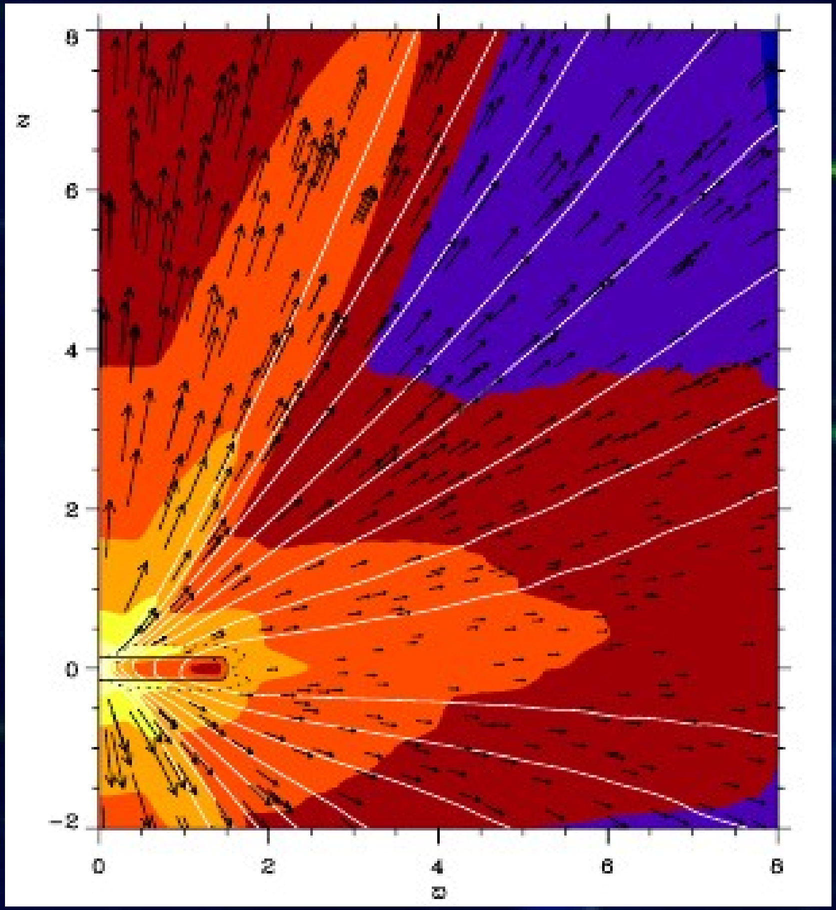
(Hirano et al 2006)



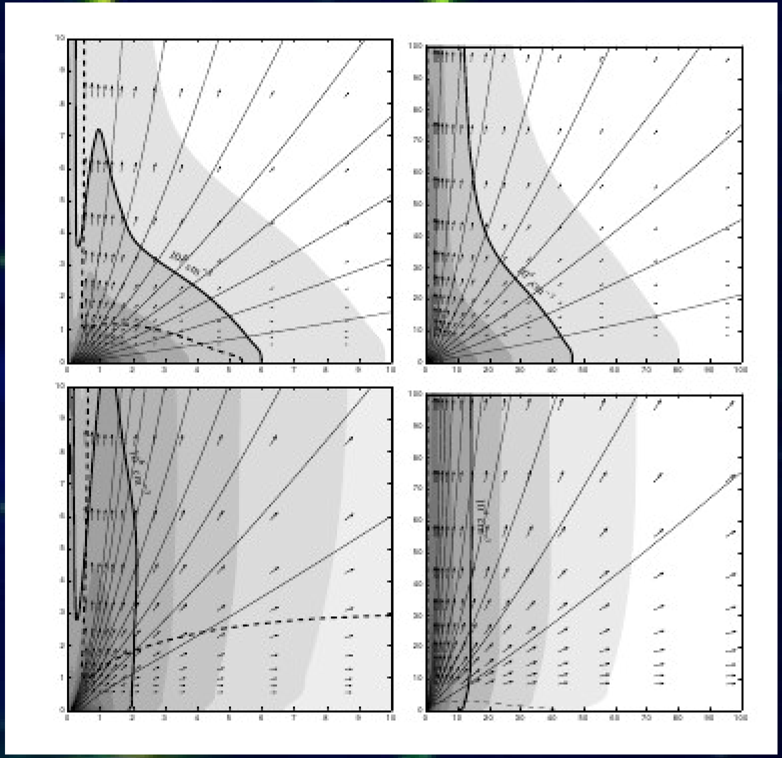


(Bachiller et al 2001)

Disks & Outflows

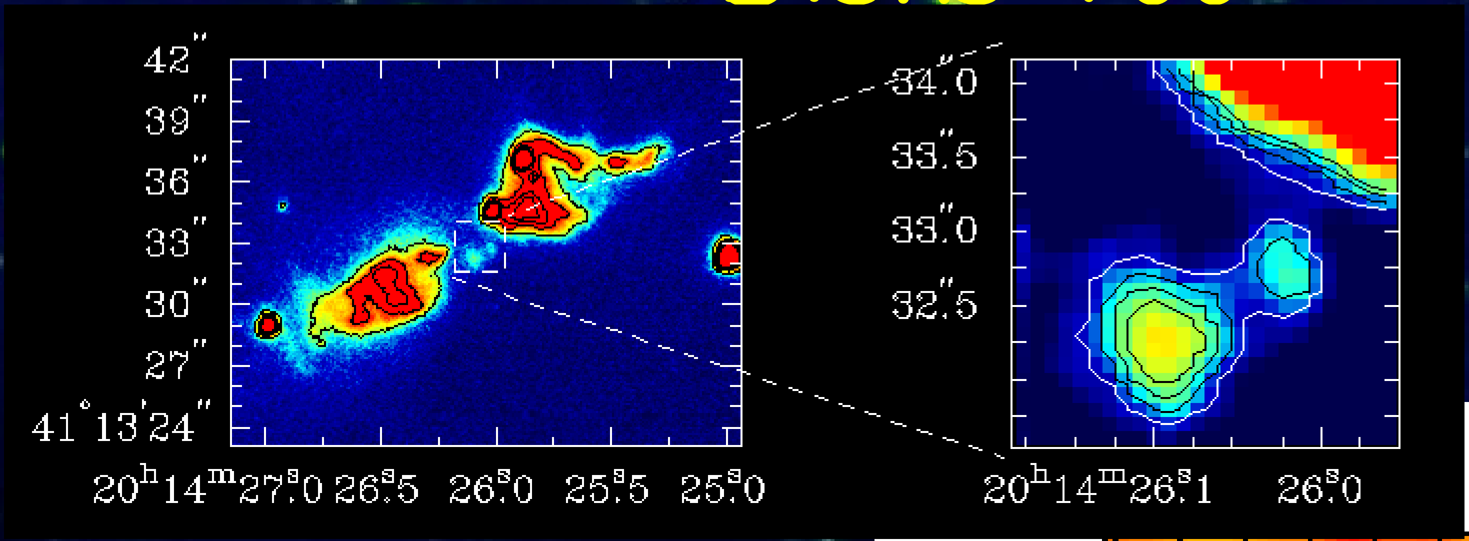


(von Rekowski et al. 2003)

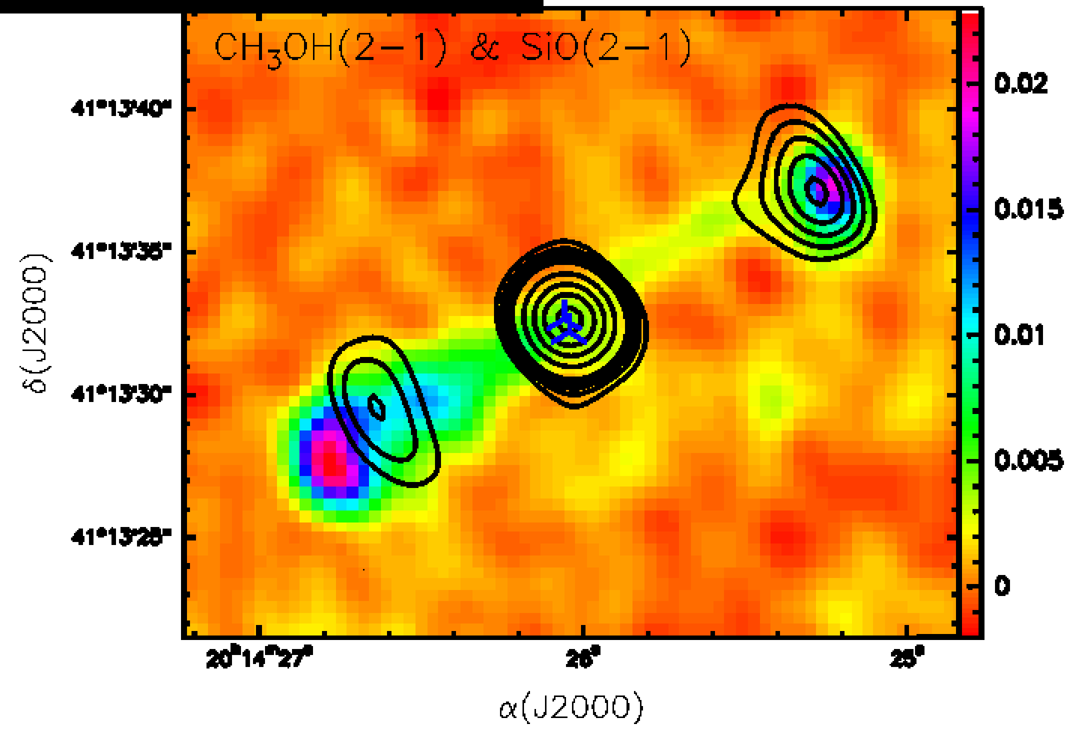


(Shang et al. 2007)

Massive Stars Have Outflows & Disks Too



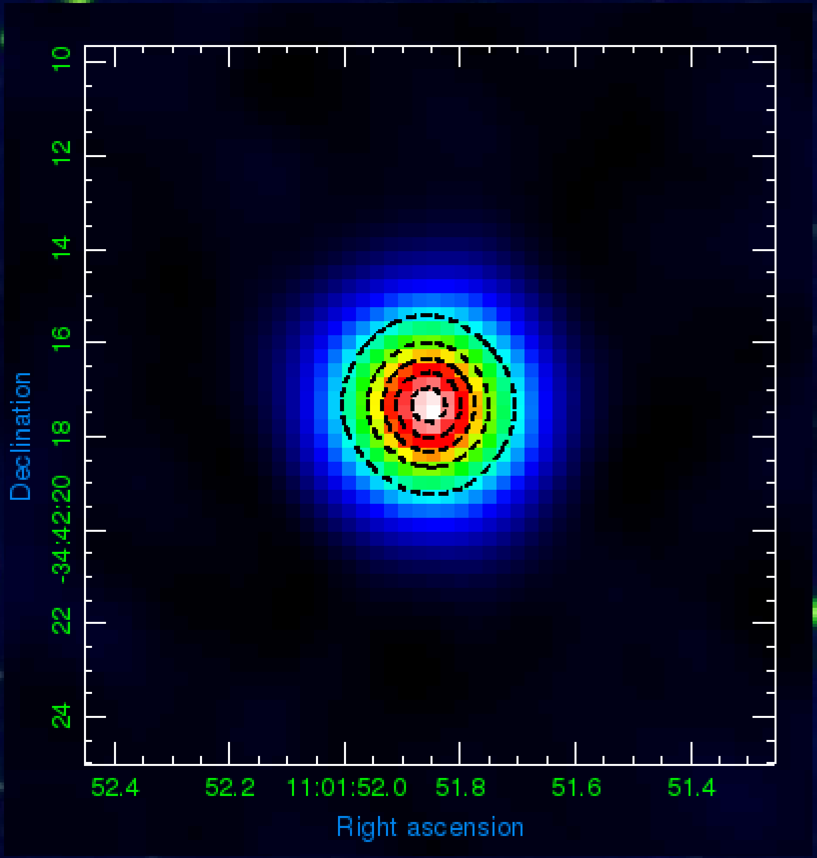
(Sridharan et al. 2006)



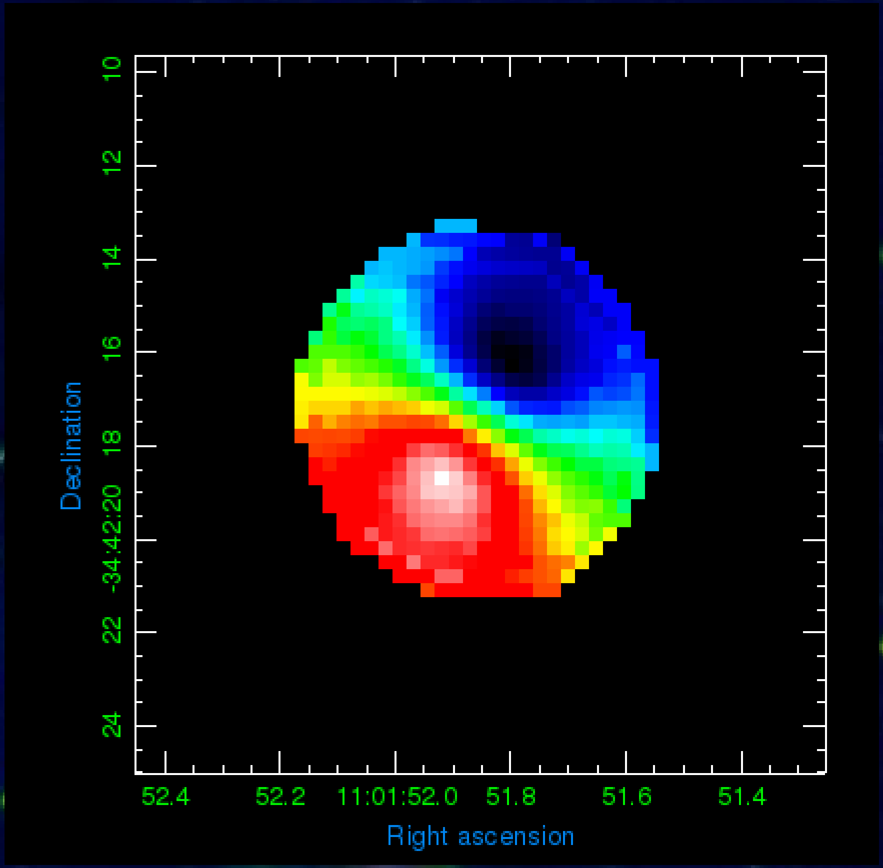
(Cesaroni et al. 2005)

Disks Around Young Stars

- ALMA observations – TW Hya



Line (HCO+ 4-3) + Continuum

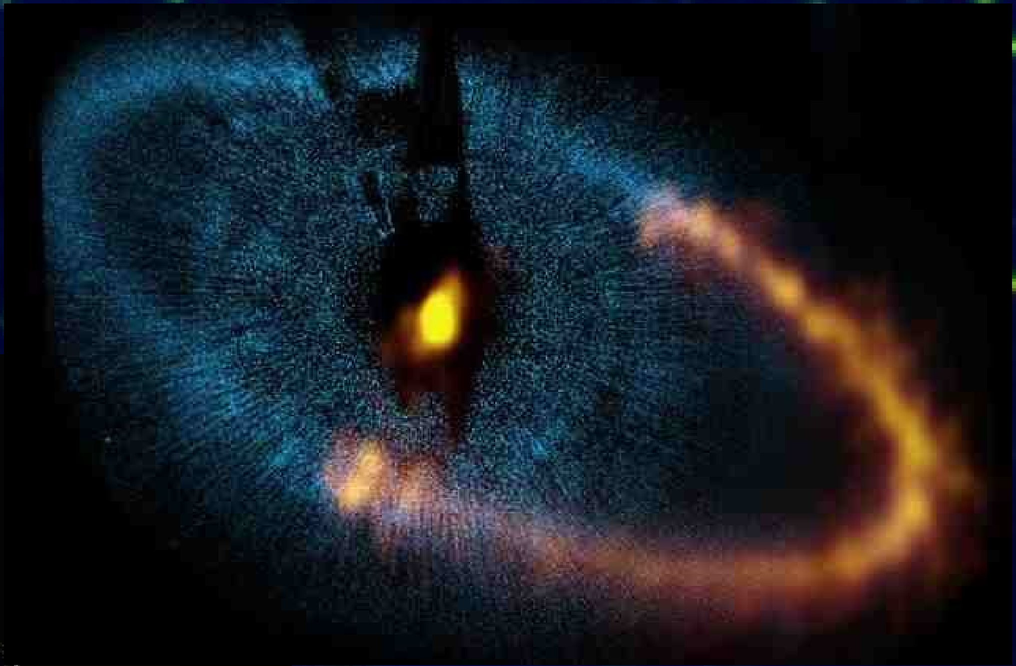


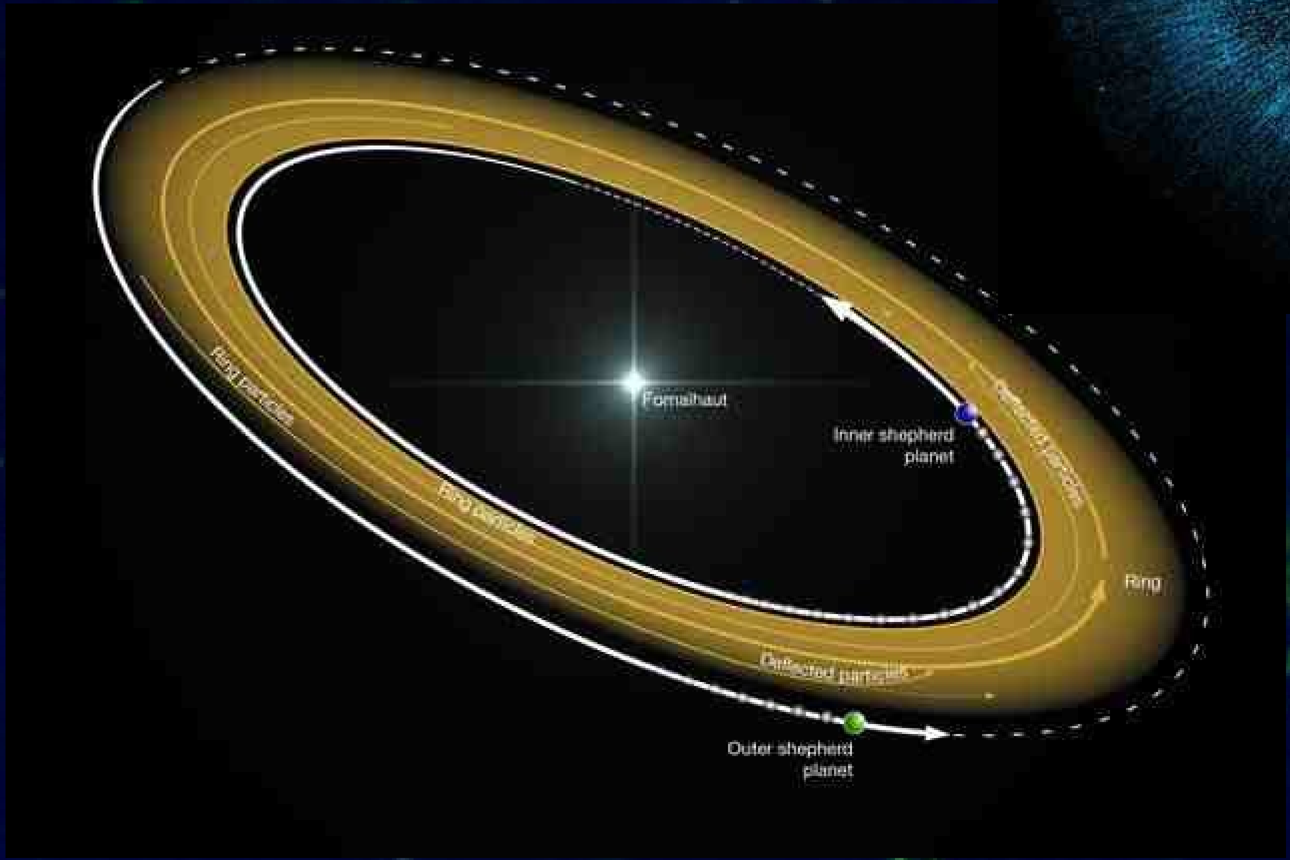
CO J=3-2, 1.5" beam, 0.2 km/s

Velocity field of gas in disk

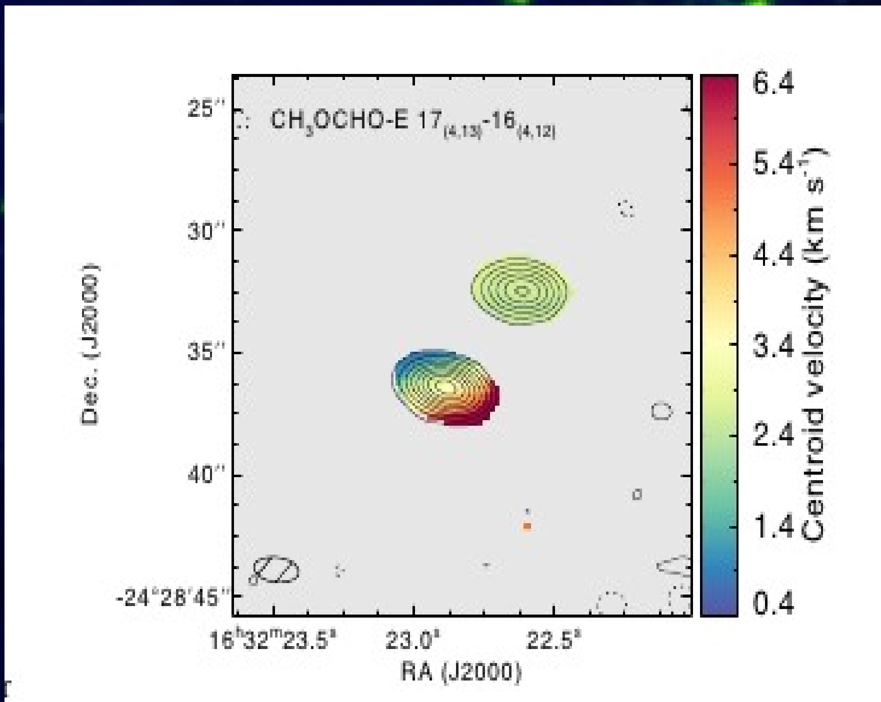
And not so young stars…
Fomalhault seen with ALMA

(Half) Dust ring confined
by two unseen planets

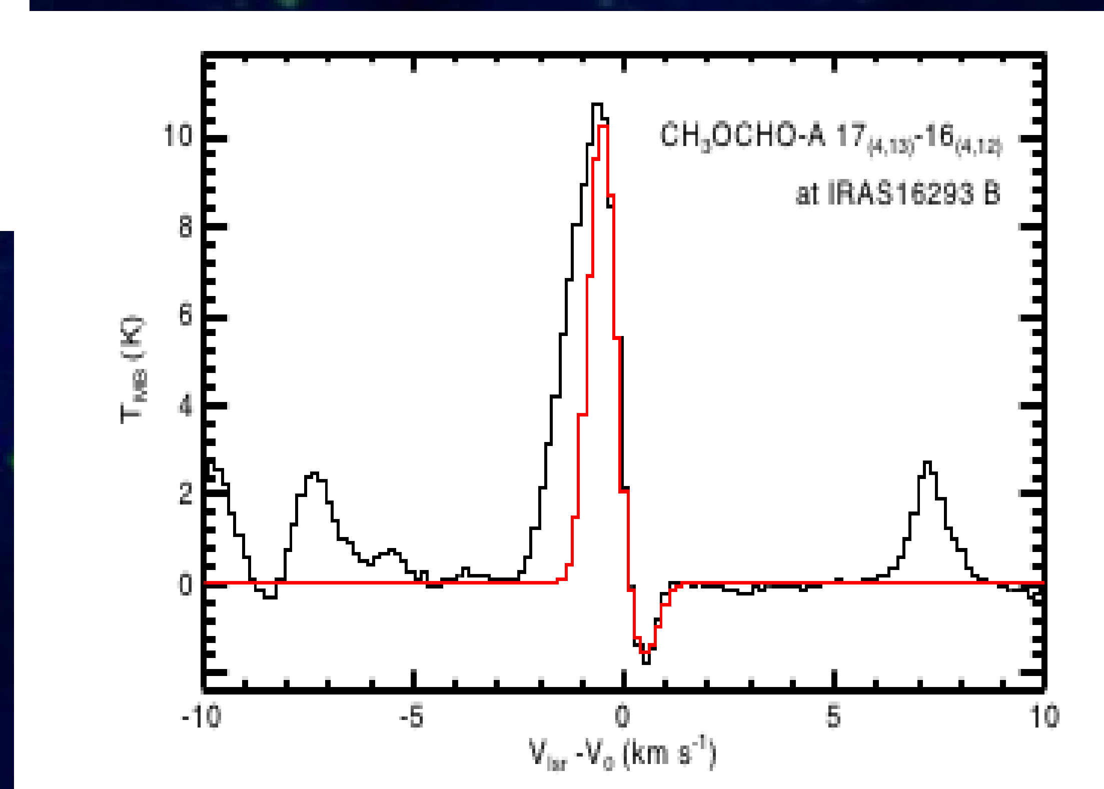




Infall Of Gas to Make the Stars

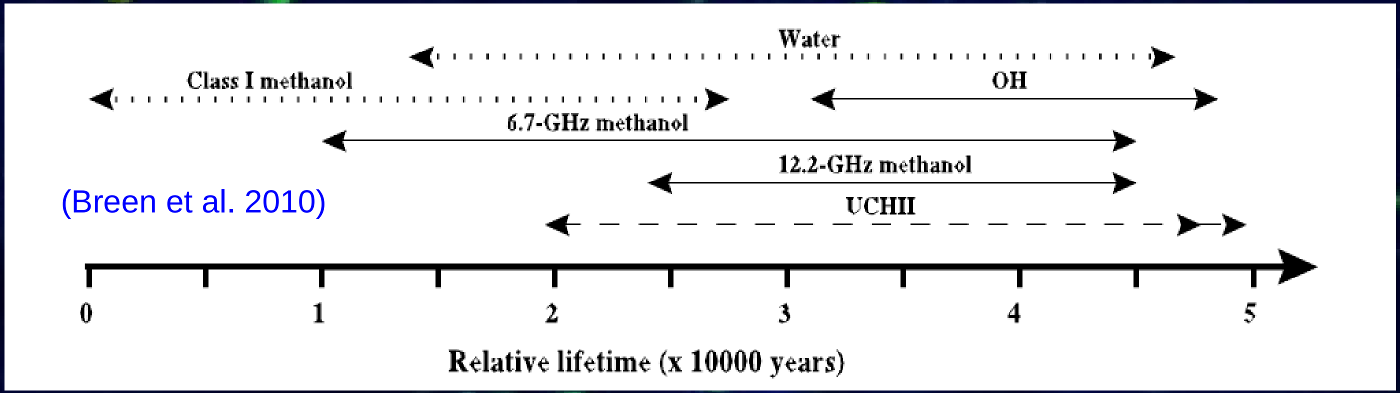


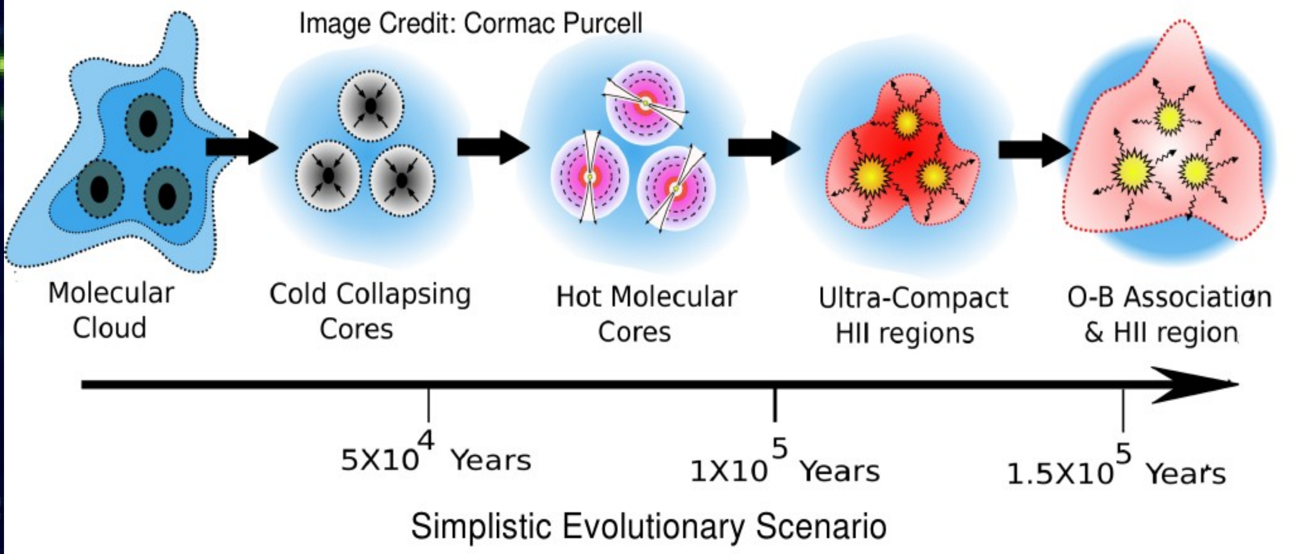
ALMA Science Verification data
Pineda et al. 2012



Protostar Evolution: High Mass

High Mass, M>10M$_{o}$

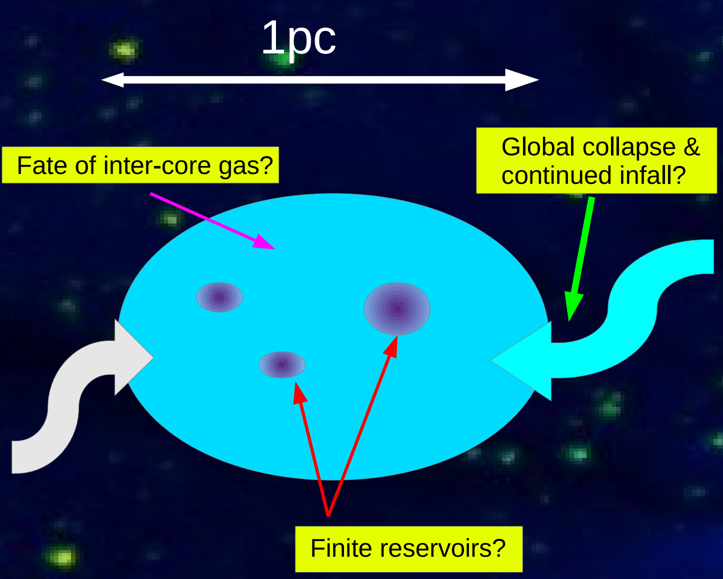




Massive Star Formation

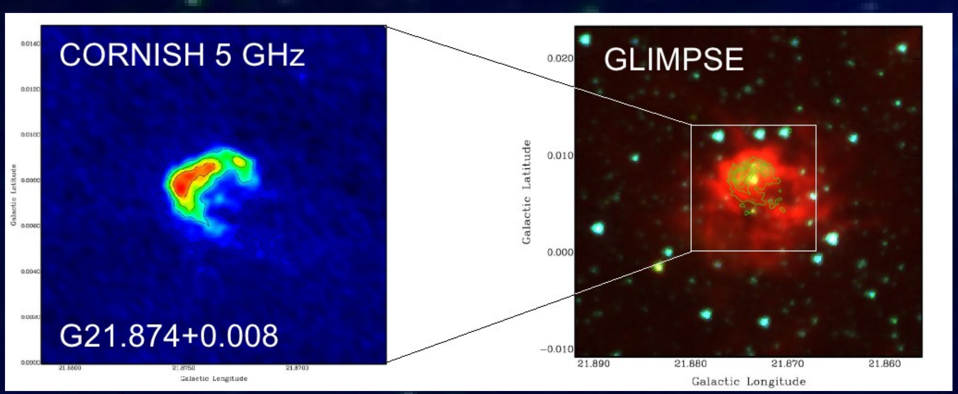
- Need to concentrate mass in to a small volume:
  - How much mass? When? From where?

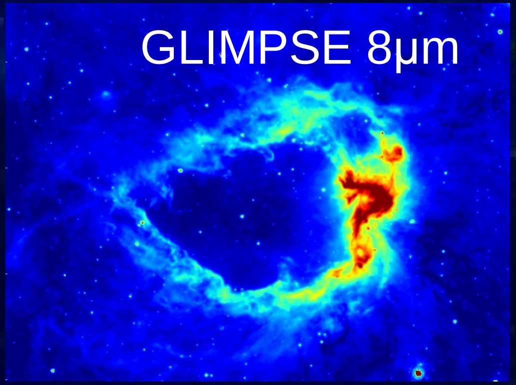
Reviews:
McKee & Ostriker 2007, ARAA
Zinnecker & Yorke 2007, ARAA



Monolithic collapse – turbulent cores:
    Myers & Fuller 1992
    McKee & Tan 2003
    Krumholz et al. 2007
Global collapse
    Smith et al. 2009
Inter-clump gas accretion/Competitive Accretion
    Bonnell et al. 1997

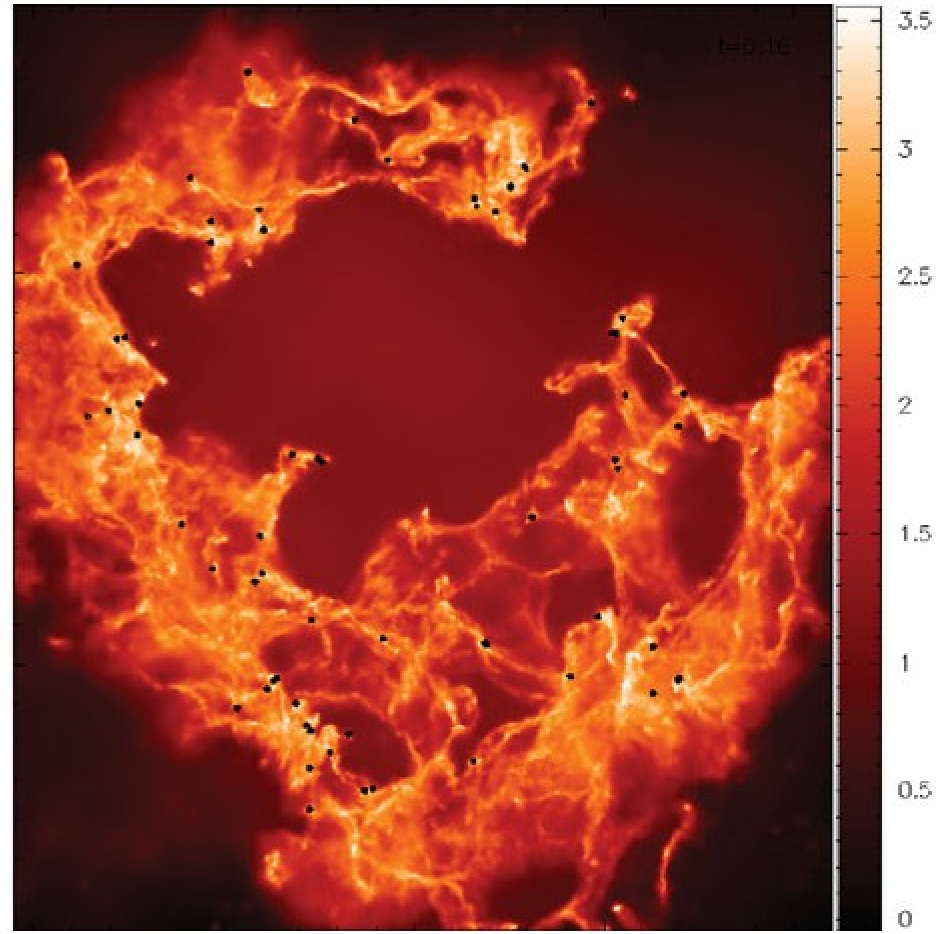
- But once the stars turn on, massive star formation becomes very messy





(Hoare et al 2012; Purcell et al. 2012)

Stellar Feedback



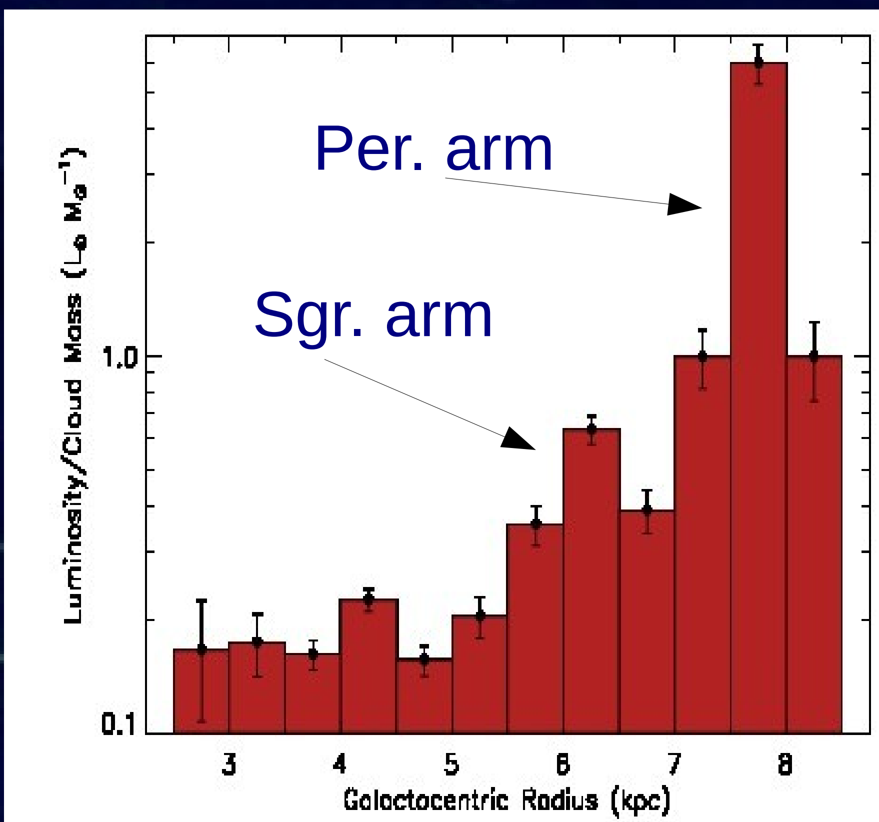
RCW79

(Walch et al. 2011)

"Star formation is a messy, complex process." I. Smail, RAS meeting 2010

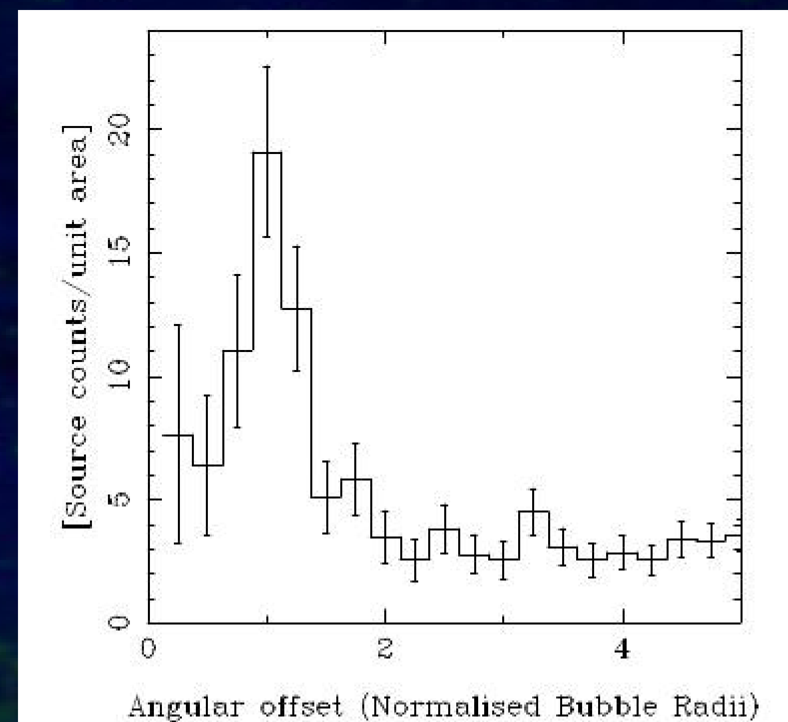
Nurture or Nature?

Higher sf efficiency in spiral arms



(Moore et al. 2011)

Higher density of sources around bubbles



(Thompson et al 2011)

Questions

- What is the structure of the densest regions of molecular clouds & how does it evolve?
- How does material move from cloud to core to star? And when?
- What determines the mass of a forming star?
- What sets the distribution of stellar masses?
- Where and how are high mass stars formed?
- What is the impact of feedback?
- How does environment affect star formation?

Need galaxy-wide samples of sources at a very early stages of evolution:

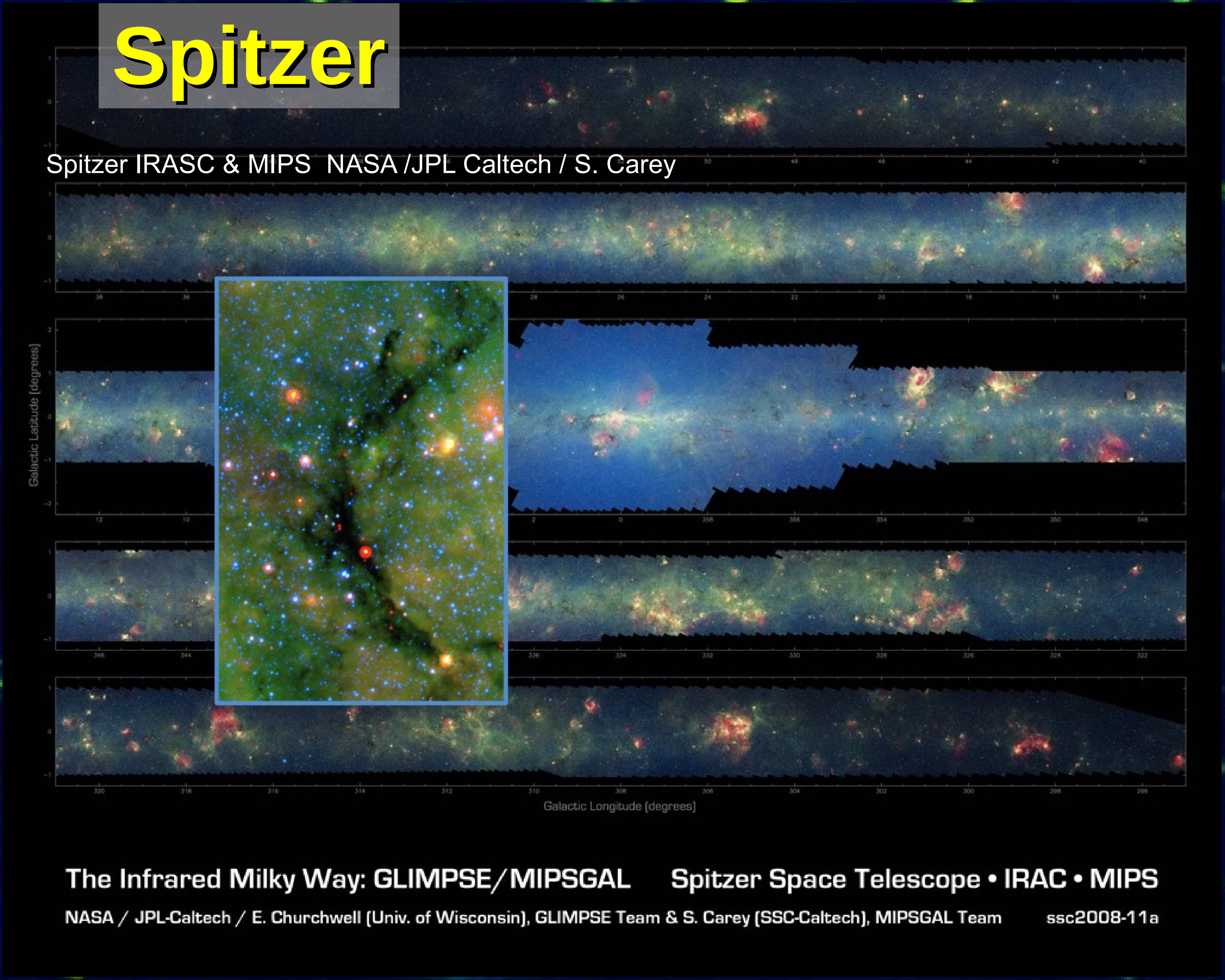
Infrared Dark Clouds (Peretto & Fuller 2009, 2010a,b)

- High column density
- But dark & so not dominated by star formation

Class II Methanol Masers (Green, Caswell, Fuller et al. 2008 - 2012)

Spitzer

Spitzer IRASC & MIPS NASA /JPL Caltech / S. Carey

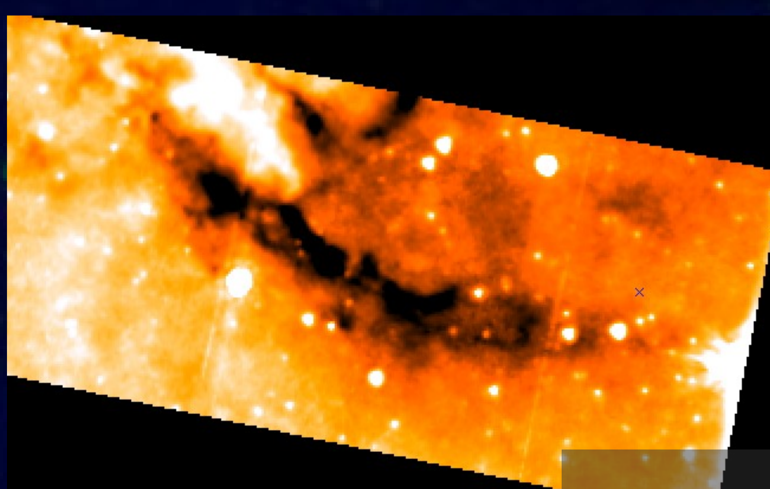


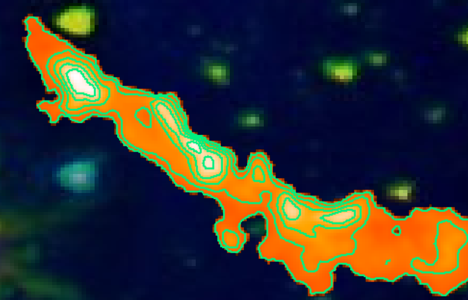
GLIMPSE I & II region: $|l|<65^{\circ}$, $|b|<1^{\circ}$

Spitzer Dark Clouds

Catalogue of Spitzer GLIMPSE 8μm identified IRDCs (Peretto & Fuller 2009, Lenfestey, Peretto & Fuller 2012)

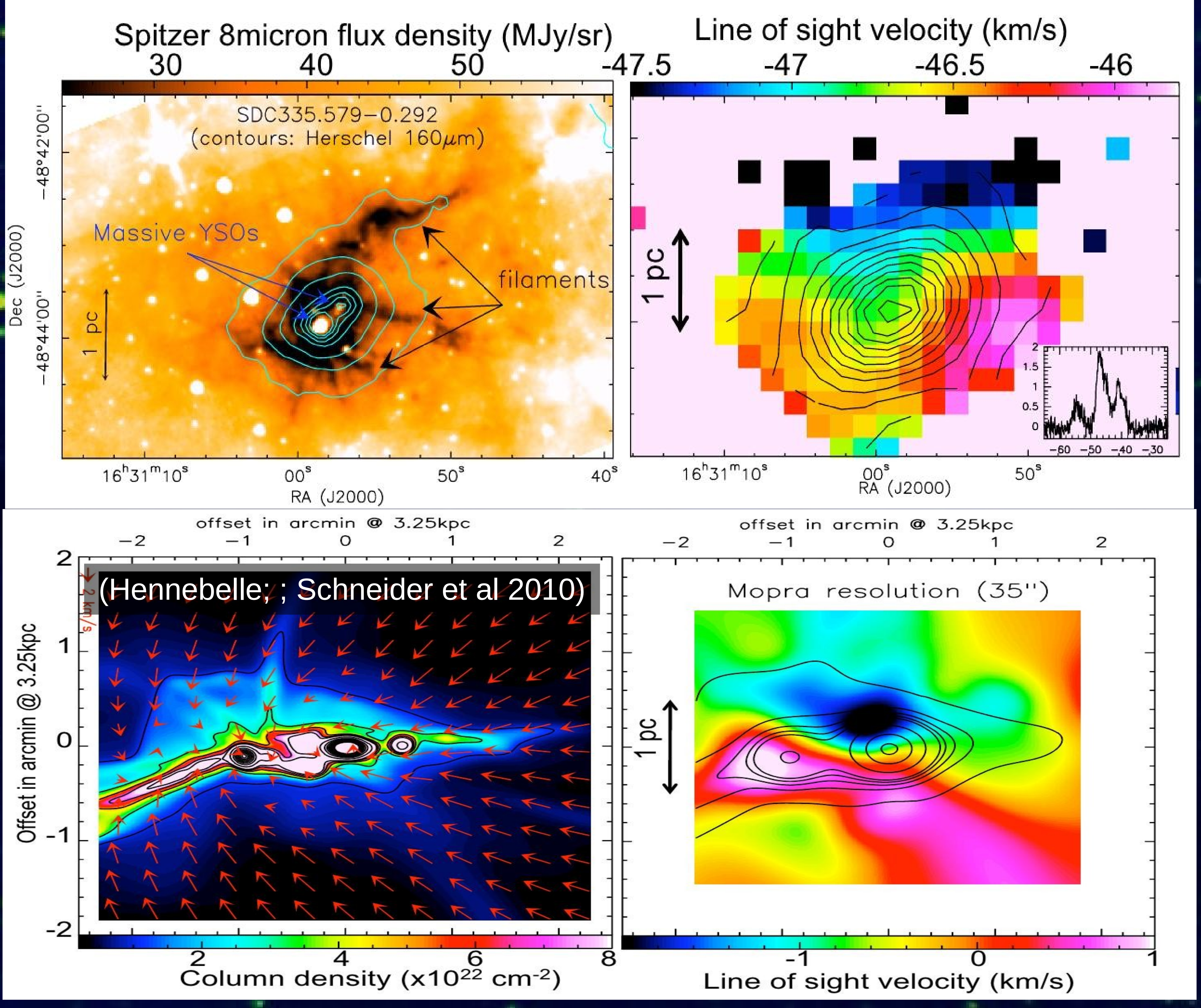
- 15,000 clouds $0^{\circ}<|l|<65^{\circ}$, $|b|<1^{\circ}$
- $A_v>10$, $N(H_2)>10^{22}$ cm^{-2}
- d>4"
- Herschel column density maps





Online database: www.irdarkclouds.org

$$\tau_{8\mu m} = -\ln\left(\frac{I_{8\mu m} - I_{\rm fore}}{I_{\rm bg}}\right)$$

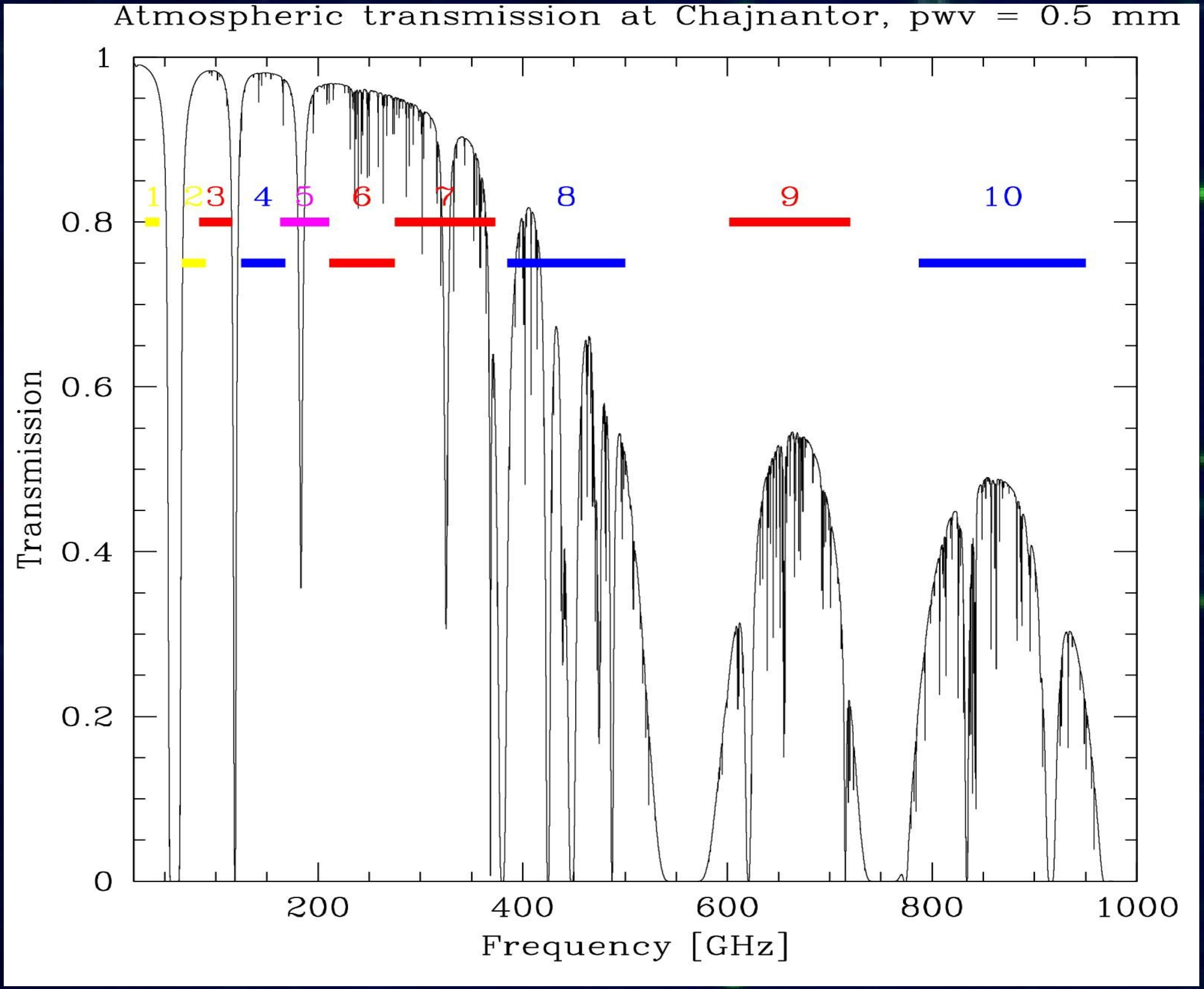


Spitzer 8micron flux density (MJy/sr)
30
40
50
SDC335.579−0.292
(contours: Herschel 160μm)
Massive YSOs
filaments
1 pc
Dec (J2000)
−48°42'00''
−48°44'00''
16h31m10s
00s
50s
40s
RA (J2000)
Line of sight velocity (km/s)
-47.5
-47
-46.5
-46
1 pc
−60 −50 −40 −30
(Hennebelle; ; Schneider et al 2010)
2 km/s
offset in arcmin @ 3.25kpc
−2 −1 0 1 2
Offset in arcmin @ 3.25kpc
2
1
0
-1
-2
Column density (x10^22 cm^-2)
2 4 6 8
Mopra resolution (35'')
1 pc
−1 0 1
Line of sight velocity (km/s)

What is ALMA?

- Atacama Large Millimetre/Sub-millimetre Array
- Aperture synthesis array optimised for millimetre and sub-millimetre wavelengths (1cm - 0.3mm/30 – 950 GHz)
- High, dry site, Chajnantor Plateau, Chile (5000m)
- International: Europe (ESO), North America (NRAO), East Asia (NAOJ) + Joint ALMA Office in Chile
- 66 antennas (12m and 7m diameter)
- Reconfigurable
- Low-noise, wide-band receivers.
- Powerful correlator - imaging and spectroscopy
- Software (dynamic scheduling, imaging, pipelines)

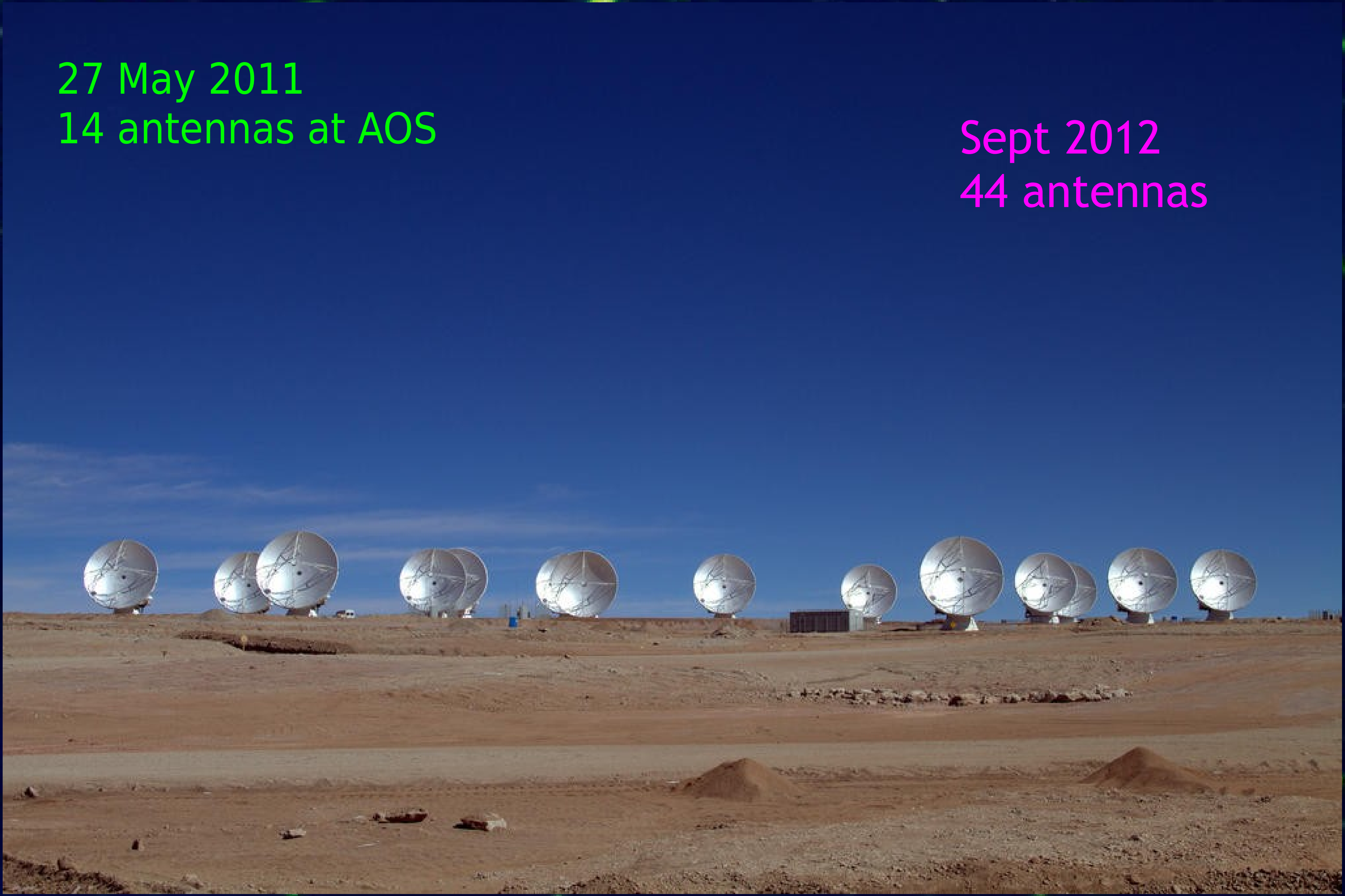
Transparent site allows full spectral coverage



Growing rapidly…

Growing rapidly...

Growing rapidly…



ALMA Data

- Band 3, N_2H^+ J=1-0, HNC J=1-0
- Compact configuration, 5" beam
- Goal: Kinematics of the filaments – Global collapse along filaments and towards protostars?

Summary

- Star formation is a messy complex, but very interesting & important process
- It produces a range of products – The key building blocks of the Universe
- Many tools available to understand it
- New instruments will revolutionize our understanding
  - Herschel – dust & gas
  - ALMA – cool dust & gas
  - eMERLIN – ionised gas & masers
  - Numerical models

Peering into the Dark
… now with ALMA

UK ALMA Regional Centre Node
www.alma.ac.uk

Books

- The Physics & Chemistry of the Interstellar Medium
  - Tielens, Cambridge University Press, 2005
- Physics of the Interstellar Medium & Intergalactic Medium
  - Draine, Princeton, 2011
- The Formation of Stars
  - Stahler & Palla, Wiley, 2004
- An Introduction to Star Formation
  - Ward-Thompson & Whitworth, Cambridge, 2011
- Principles of Star Formation
  - Bodenheimer, Springer, 2011
- Accretion Processes in Star Formation
  - Hartmann, Cambridge, 2008
-