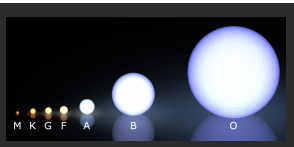
MAITE BELTRÁN
INAF-OSSERVATORIO ASTROFISICO DI ARCETRI

PERSPECTIVES ON STAR FORMATION: THE FORMATION OF HIGH-MASS STARS

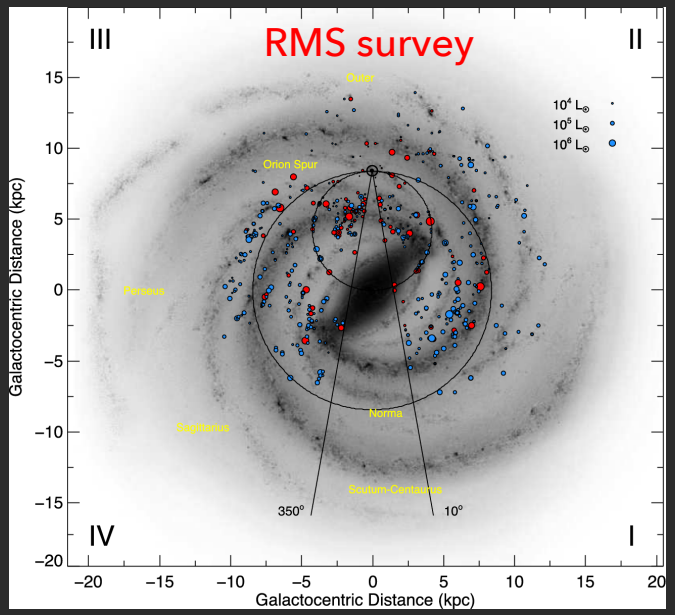
OUTLINE

1. Basic properties
2. Challenges
3. Theoretical models
4. Evolutionary stages
5. The earliest phases

1. BASIC PROPERTIES

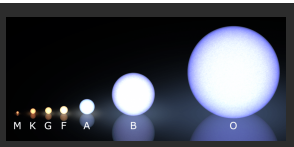


- High-mass stars have masses > 8-10 $M_\odot$
- Luminosities > 10^4 times higher than low-mass. Total luminosity dominated by high-mass stars.
- For each 30 $M_\odot$ star, there are 100 stars with1 $M_\odot$ (Salpeter's IMF).
- Short evolutionary timescales ~10^5 yr (McKee & Tan 2002): thousands of times shorter than low-mass stars (Sun: ~10^7 yr). And short lifetimes.
- Mainly located in the spiral arms of the galaxies, in which they formed because of their short lifetimes .
- Key elements in galaxies, they dominate their appearance and evolution.
- They are responsible for the production of heavy elements and influence the interstellar medium though energetic winds and supernovae. Produce enough UV to create HII regions.
- High-mass star-forming cores are the most chemically rich sources in the Galaxy and best reservoirs of Complex Organic Molecules, in particular prebiotic ones (building blocks of life).



Urquhart+ (2014)

1. BASIC PROPERTIES



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N90 in SMC

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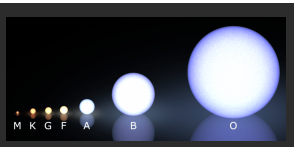

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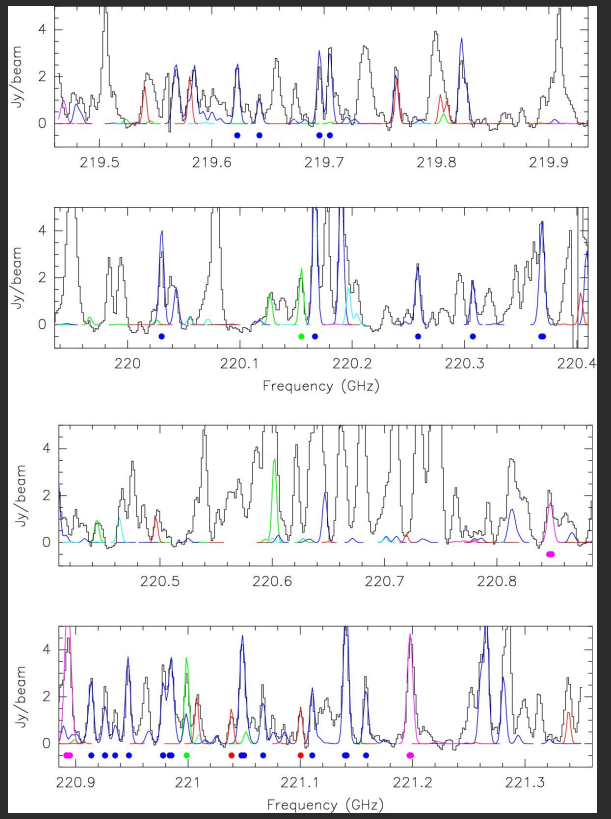
G31.41+0.31



Rivilla+ (2017)

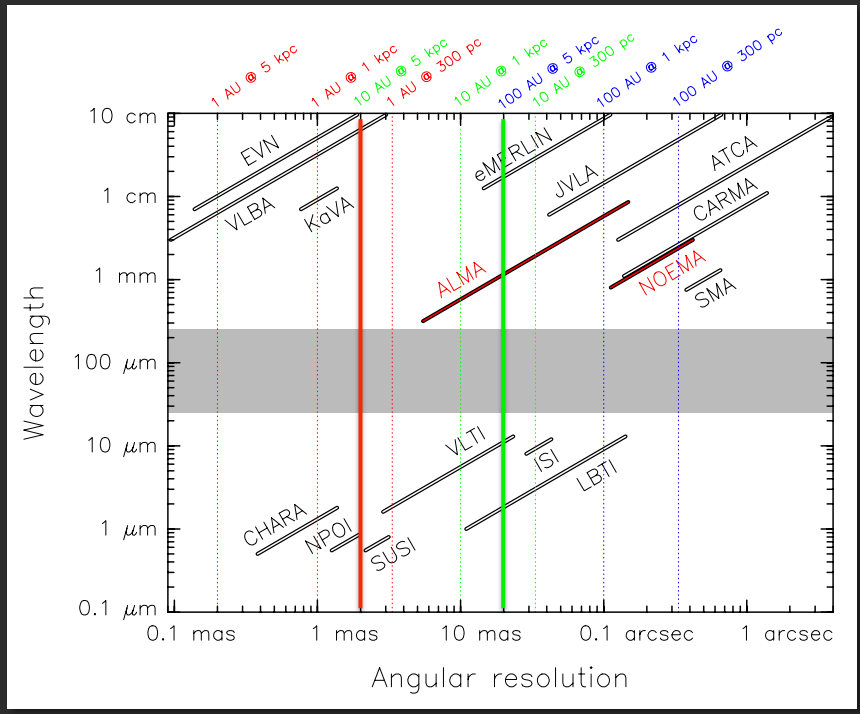
methanol, methyl cyanide, methyl formate, ethanol, dimethyl ether, glycolaldehyde, ethylene glycol …



OBSERVATIONAL

- Massive stars are rare objects found at large distances ➔ 5 kpc
- Short lifetimes, difficult to trace the earliest phases
- Massive stars embedded in rich clusters: only ~4% of O-field stars might have formed outside (de Wit + 2005).Emission difficult to disentangle and confusion with other cluster members.
- Difficult to trace the primordial configuration of the molecular cloud and obtain the initial conditions.

HIGH-ANGULAR RESOLUTION AT CM-MM λ's IS A PRE-REQUISITE



Beltrán & de Wit (2016)

THEORETICAL

- Two relevant timescales in star formation:

  accretion $t_{acc} = M_*/(dM_*/dt)$

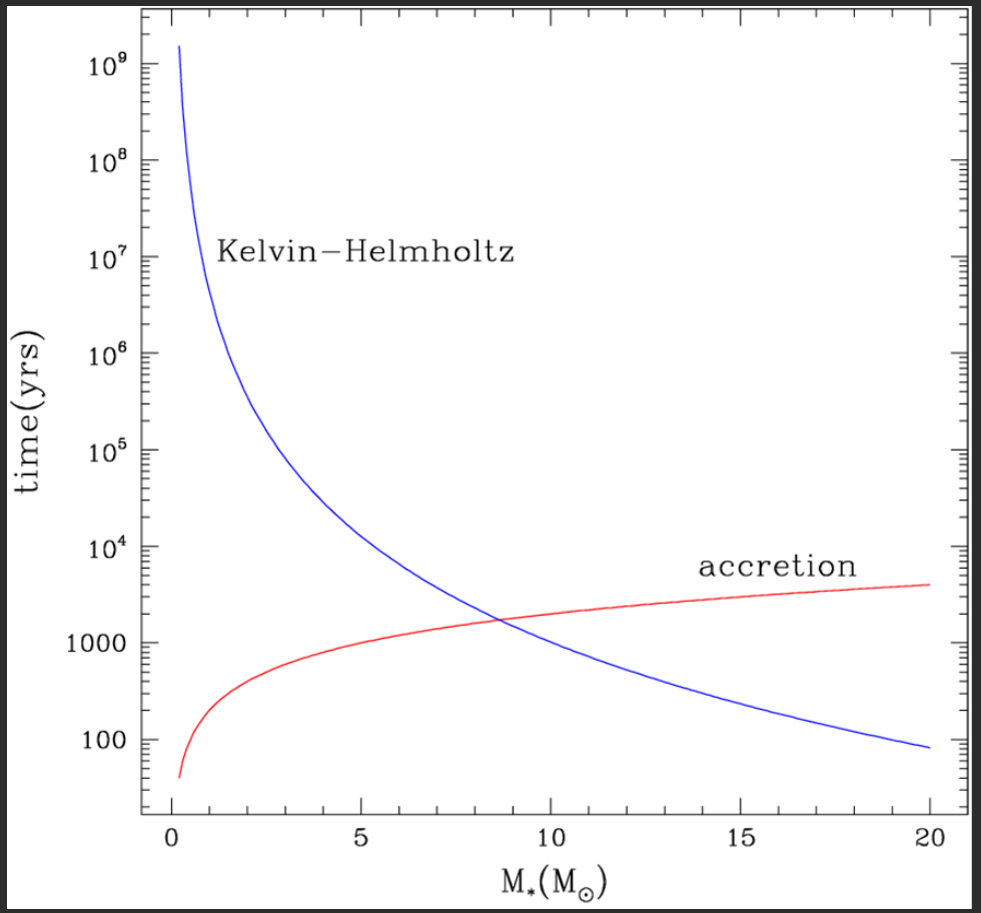
  contraction $t_{KH} = GM_*/R_*L_*$

- Low-mass (< 8 $M_\odot$): $t_{acc} < t_{KH}$

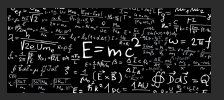
  ➡ Pre-main sequence

- High-mass (> 8 $M_\odot$): $t_{acc} > t_{KH}$

  ➡ No pre-main sequence, accretion on ZAMS



Radiation pressure acting on dust grains become large enough to reverse the infall of matter

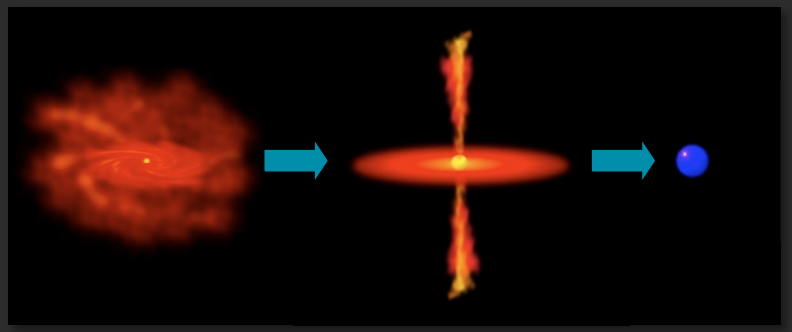


MONOLITHIC COLLAPSE VS. COMPETITIVE ACCRETION

- MONOLITHIC COLLAPSE: McKee & Tan (2002, 2003,2004)

  1 core → 1 massive star

stars form via a monolithic collapse of a massive turbulent core: a massive star forms from a massive core and gathers its mass from this massive core alone. Given the non-zero angular momentum of the collapsing core, this model predicts the existence of protostellar accretion disks around massive stars.

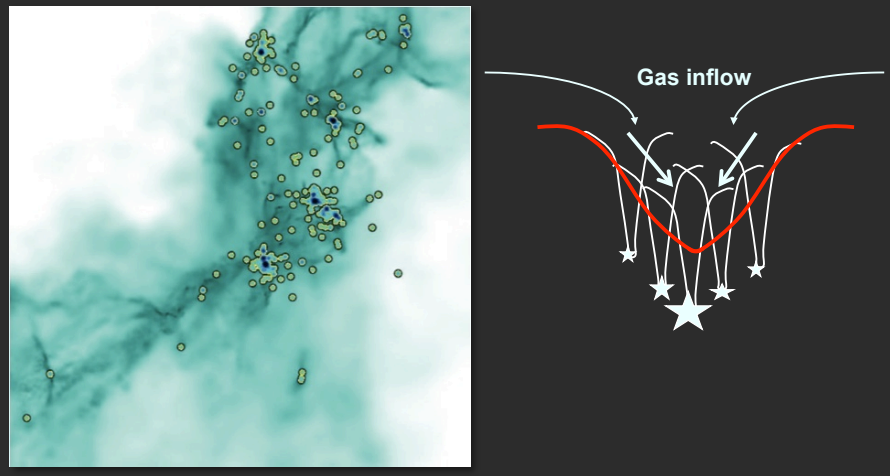


Courtesy of Luca Carbonaro

- COMPETITIVE ACCRETION: Bonnell et al. (1997, 2001, 2004)

  Fragmentation in multiple cores

clouds fragment initially into cores of a Jeans mass of ~0.5-1 $M_{\odot}$. These cores subsequently form low-mass stars that compete to accrete the distributed gas in the molecular clump. This models predicts that massive stars should form exclusively in clustered environments. A special case of interaction is that causing a merging between low-mass stars, which is only predicted for unusually high stellar densities.



Adapted from Bonnell (2004)



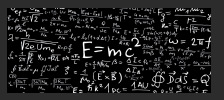
MONOLITHIC COLLAPSE VS. COMPETITIVE ACCRETION

MONOLITHIC COLLAPSE

- 1 core → 1 massive star (or small multiple systems).
- Stellar mass pre-assembled in the collapsing core (isolated from rest of the cloud).
- Isolated massive star formation
- CMF similar to IMF
- Turbulent medium (high accretion rates: $\dot{M} >> 10^{-5}\ M_{\odot}$/yr).
- Slow, quasi-static process
- Initial conditions: strongly peaked density distribution ($n\ \alpha\ r^{-1.5}$)
- Disks and outflows should exist

COMPETITIVE ACCRETION

- Fragmentation in multiple cores of thermal Jeans mass.
- Accretion of unbound gas from whole cloud (global collapse). No connection between mass of the core and final stellar mass.
- Massive stars always form in clusters. Most massive star at the center
- Lead to full IMF
- Bondi-Hoyle accretion ($\dot{M} \sim M^2$).
- Fast, dynamical process, gravity driven
- Initial conditions: uniform gas density
- Disks exist (1000s au) but are disturbed and semi-transient structure. Chaotic orientations



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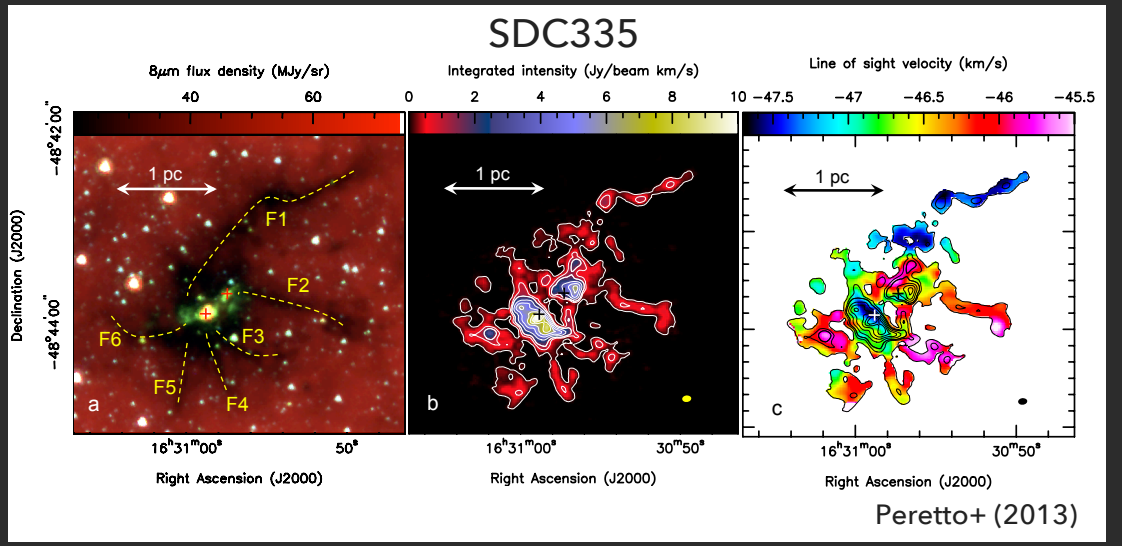

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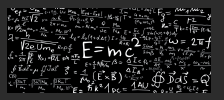

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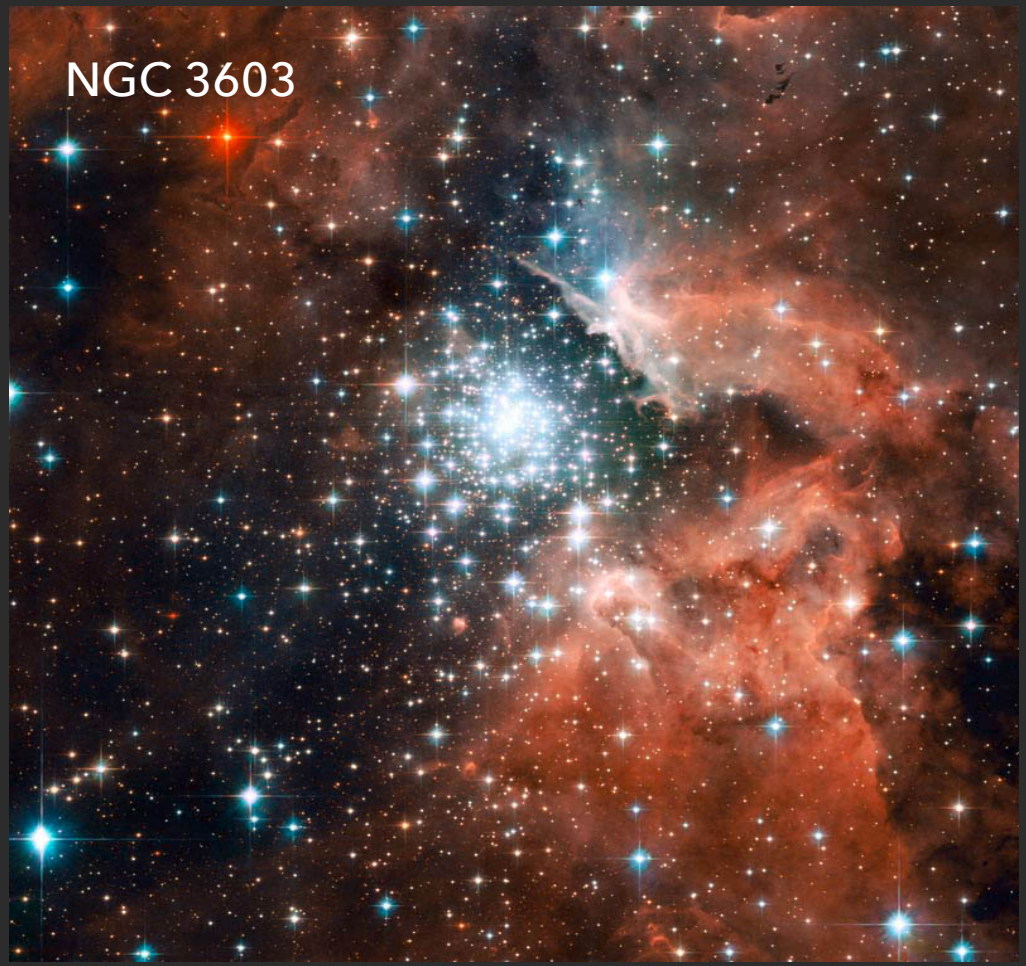



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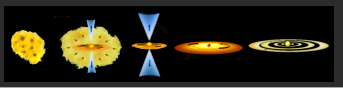
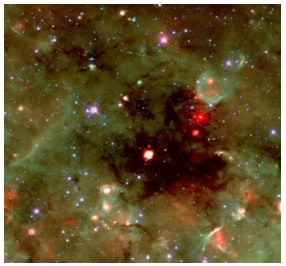
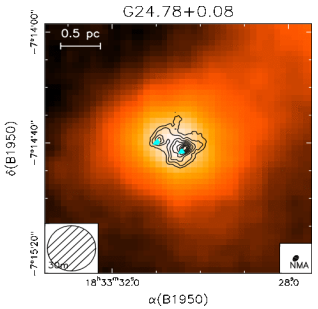
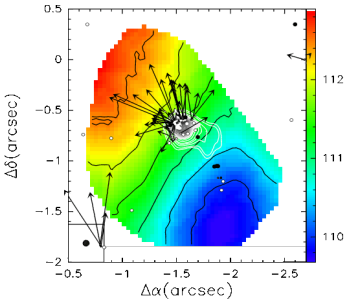
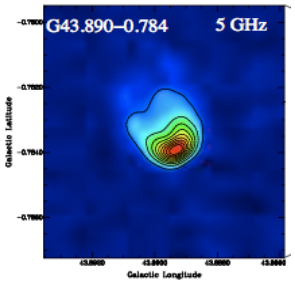
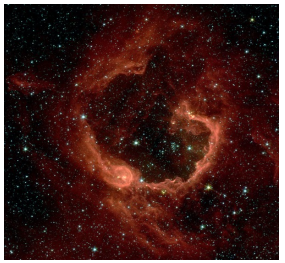
4. EVOLUTIONARY SEQUENCE



ENVIRONMENT

IR-dark cloud	Hot molecular core	HC HII	UC HII	Extended HII
				

PHENOMENA

fragmentation	infall+rotation+outflow	accretion + outflow	expansion

YSO

high-mass pre-stellar core	Proto-stellar object low → intermediate → high-mass	main-sequence star

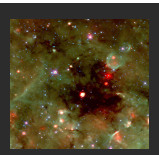
MASERS

CH_3OH Class I

CH_3OH Class II

H_2O

OH

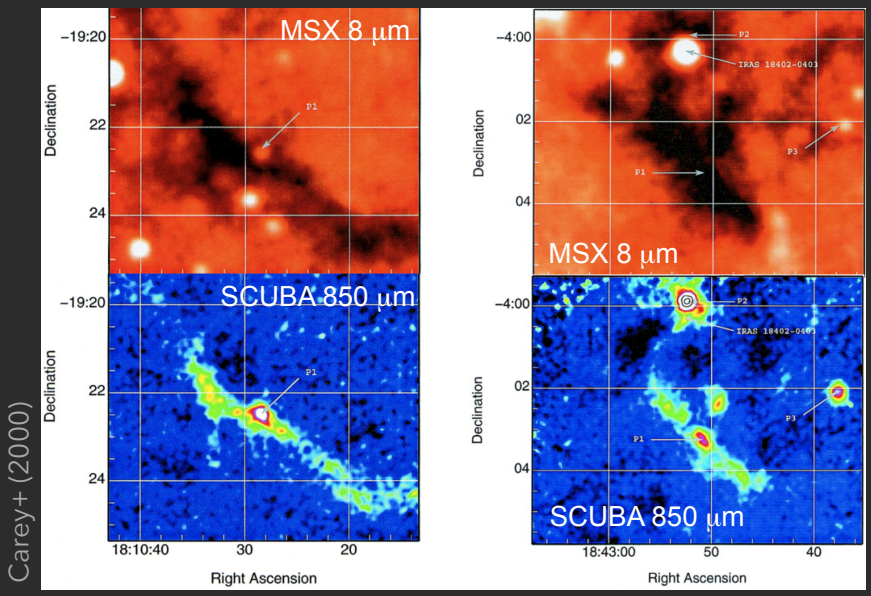


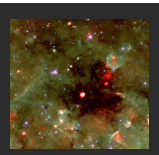
IRDCs

- Massive stars form in parsec scale high-density clumps (10^4 to 10^5 cm^{-3}) within Giant Molecular Clouds (GMCs) (density of order 100-1000 cm^{-3}) ➔ IR-Dark Clouds (IRDCs)

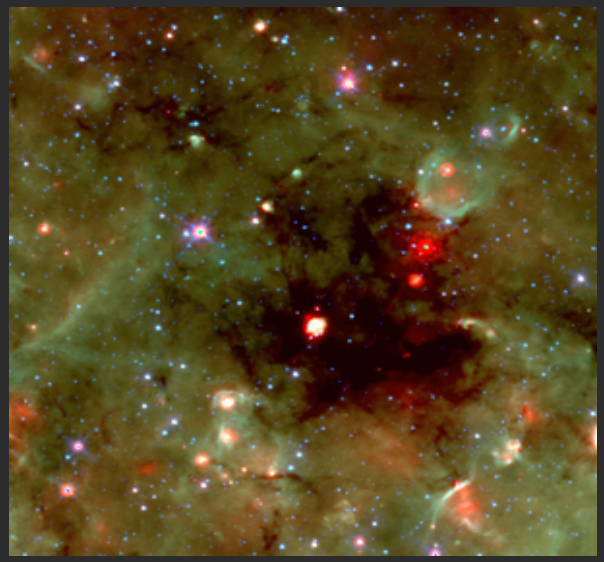
- IRDCs are detected in absorption at 8 μm and up to 24 mm (70 μm) with Spitzer, MSX, Herschel (Egan et al. 1998, Carey et al. 1998), and emission at (sub)mm λ's.

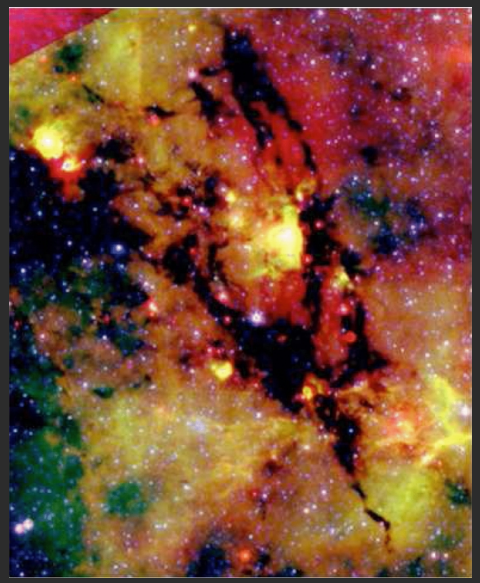
- Properties:
  - sizes 1-5 pc
  - M~10^3-10^4 $M_\odot$
  - n~10^5 cm^{-3}
  - T < 20 K

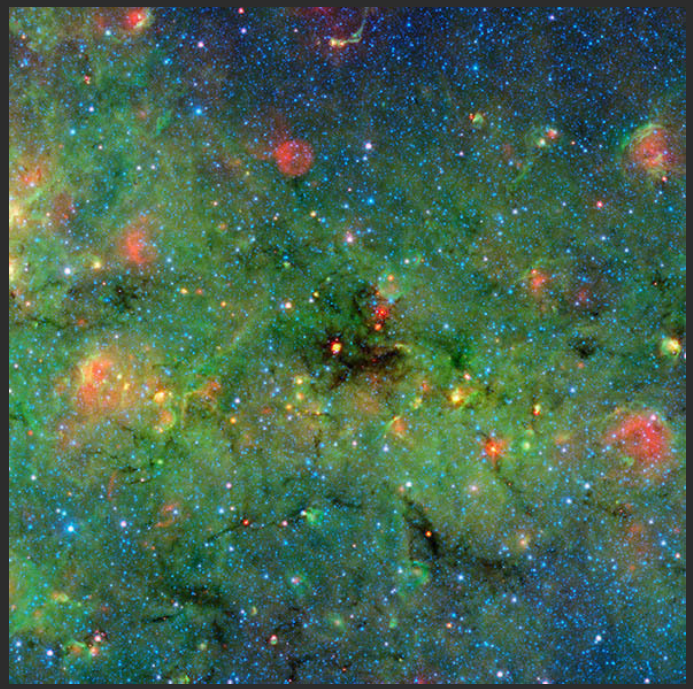


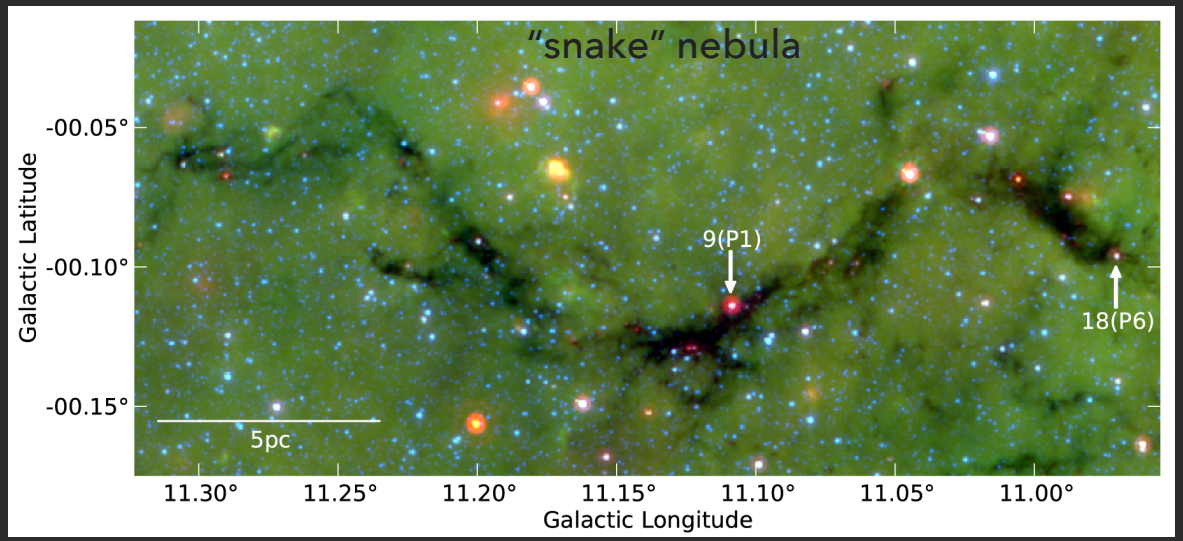


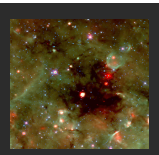
IRDCs: morphology











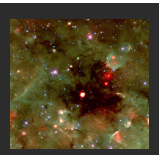
IRDCs: filamentary structure



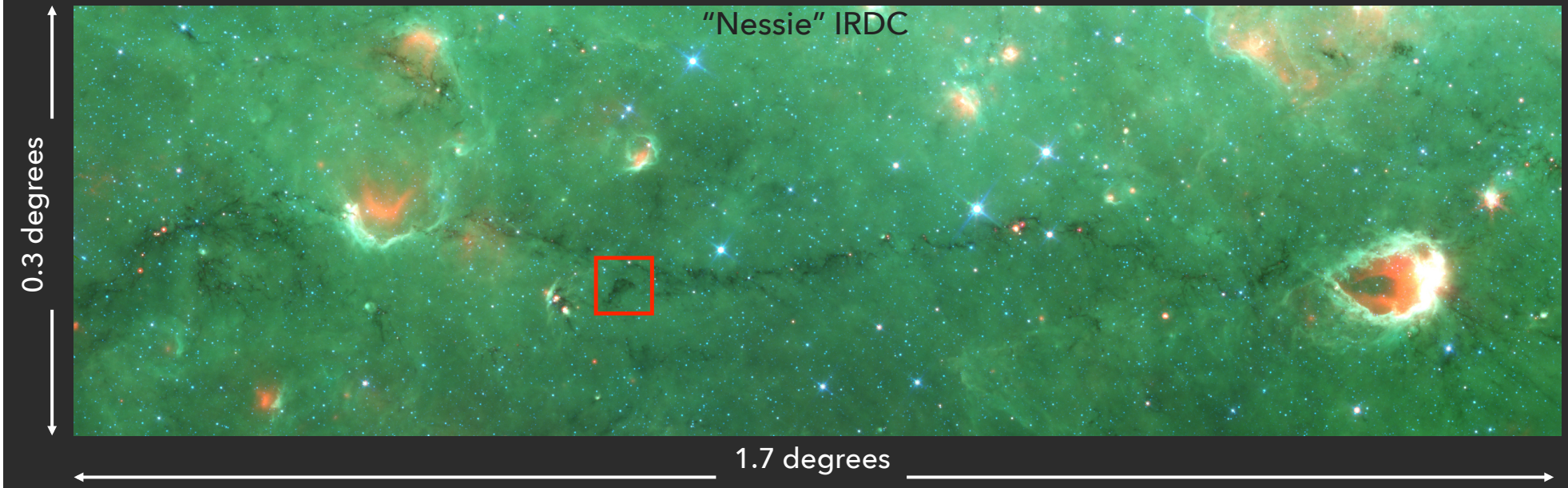
Spitzer 4.5/8/24 μm

100 pc x 0.5 pc

Adapted from J. Jackson

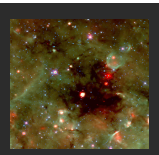


IRDCs: not an evolutionary phase



pre-stellar core candidate

Adapted from J. Jackson



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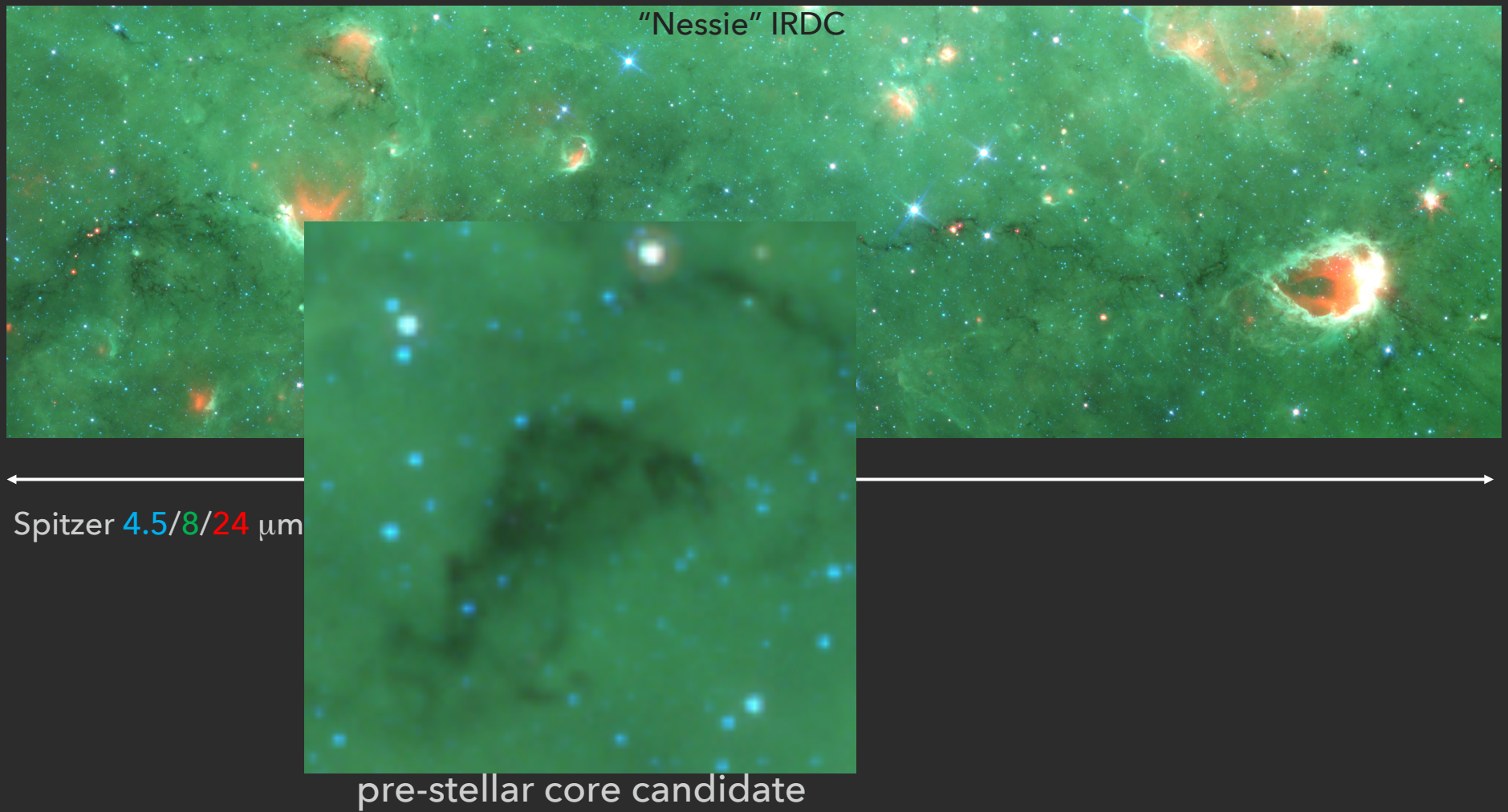

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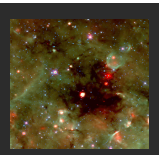

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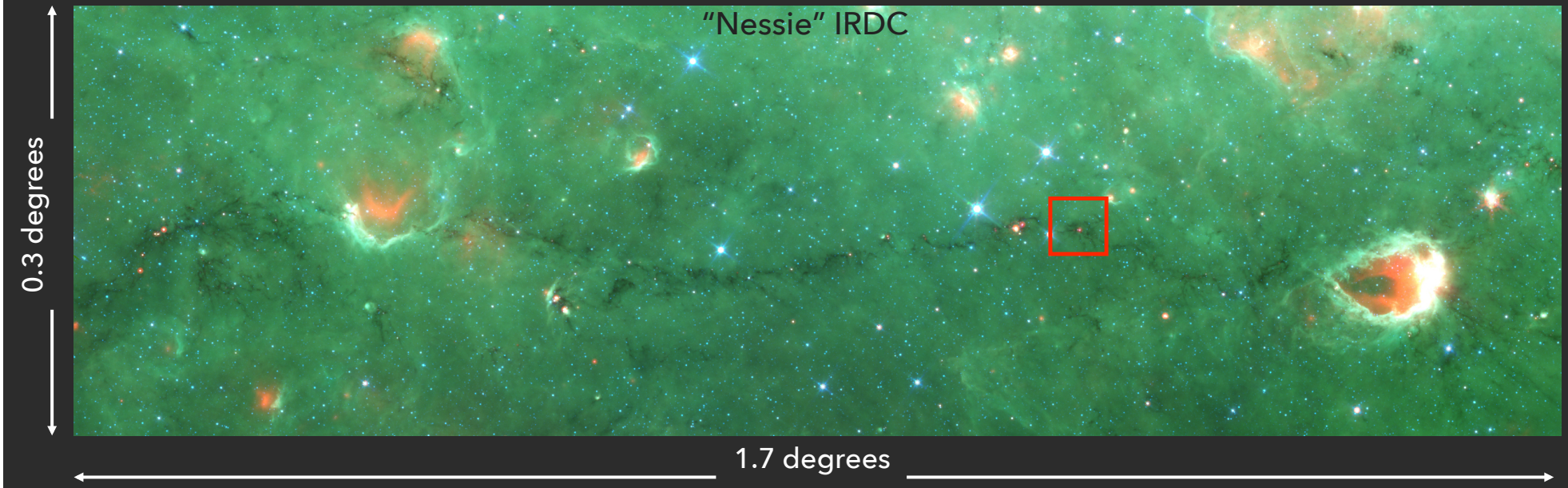
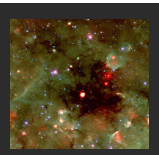


Spitzer 4.5/8/24 μm

Proto-stellar object

Adapted from J. Jackson



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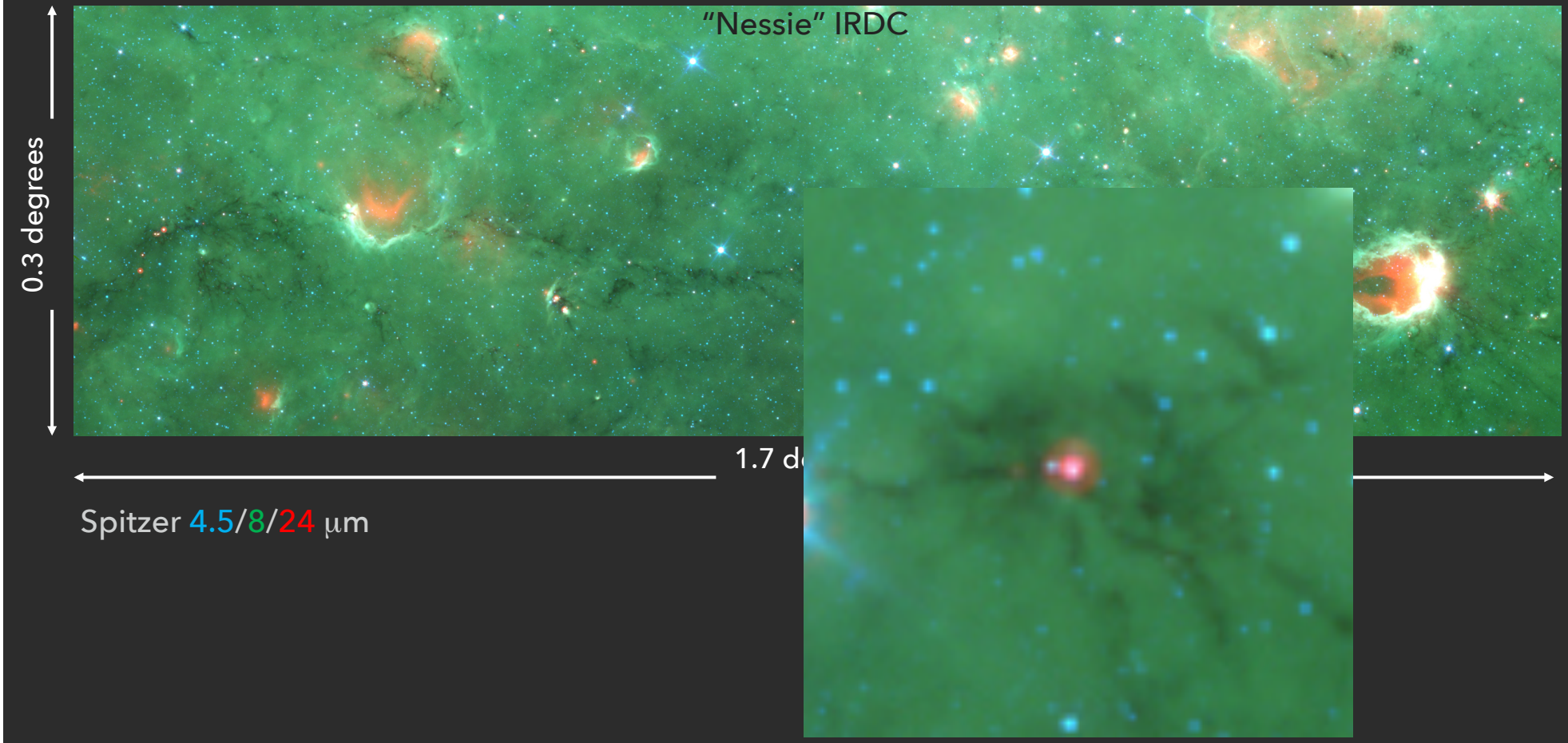

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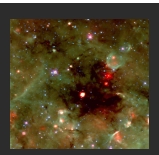

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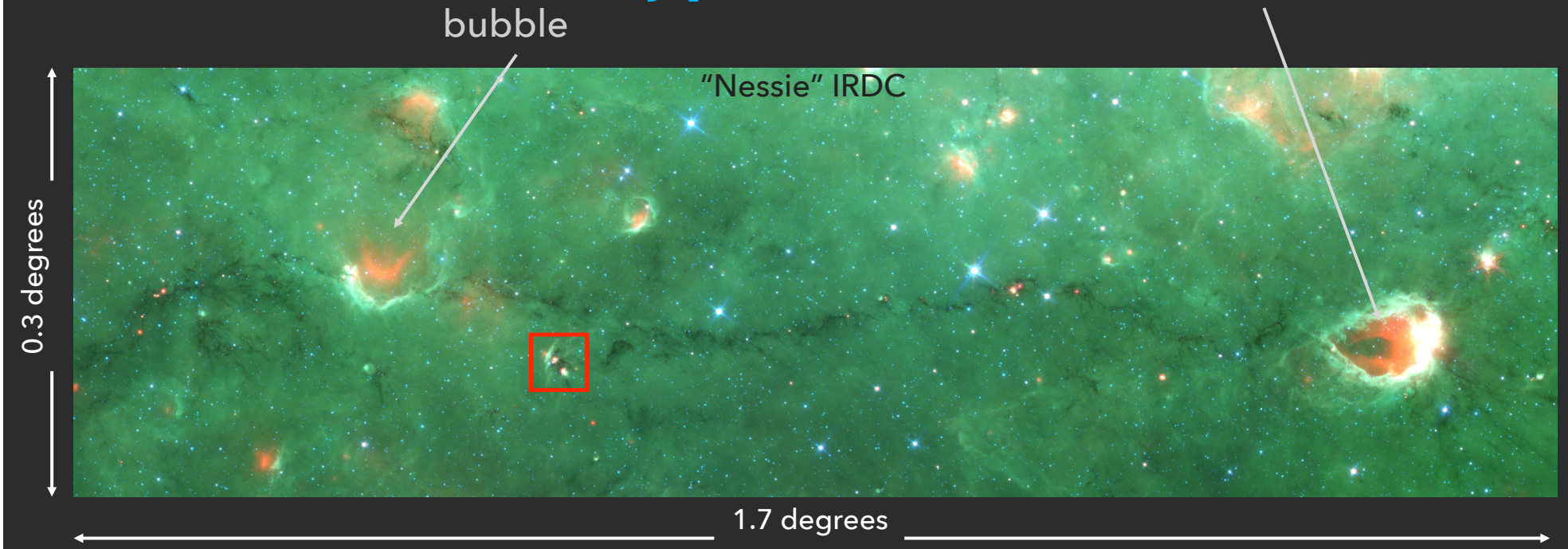
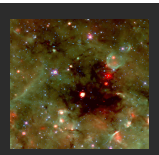


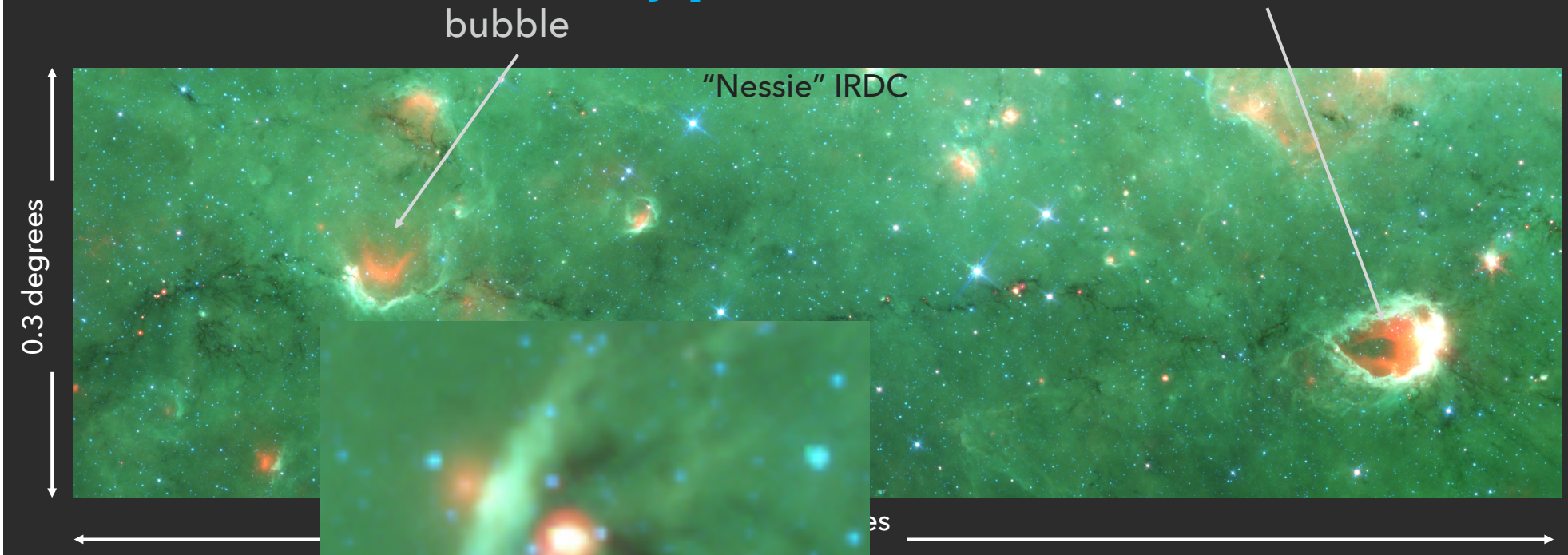
Spitzer 4.5/8/24 μm

HII region

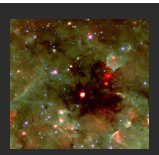
Adapted from J. Jackson



IRDCs: not an evolutionary phase

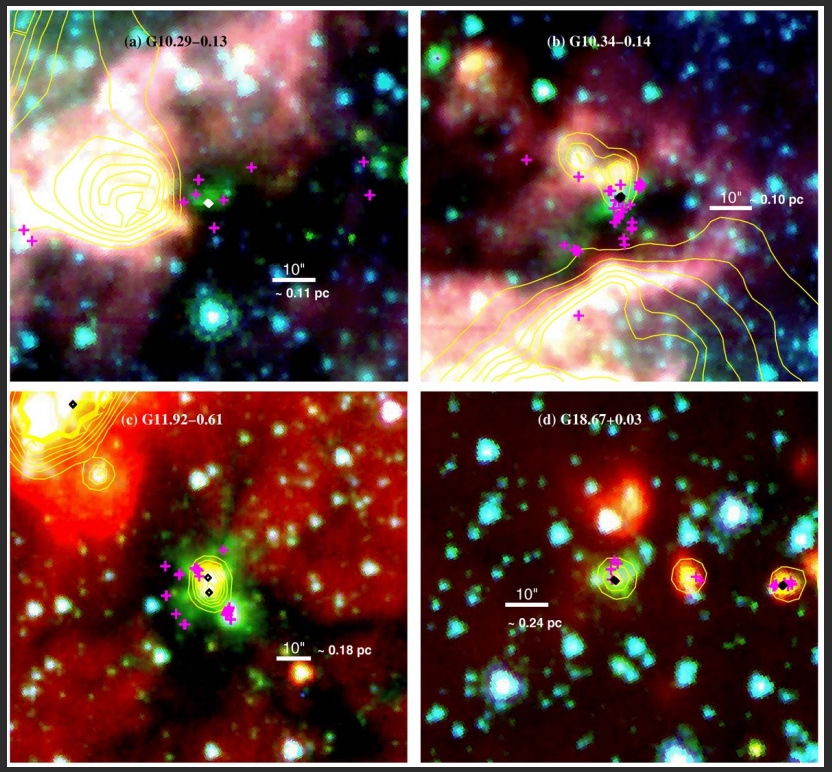


Adapted from J. Jackson



IRDCs: pre-stellar cores?

- Many IRDCs show evidence for active star formation
- Extended 4.5 μm emission called "green-fuzzies", broad SiO emission, maser emission, → molecular outflows
- Bright, compact 24 μm emission associated with deeply embedded protostar.
- Bright 8 μm (red sources) associated with HII regions



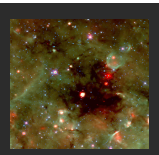
Cyganowski+ (2009)

GLIMPSE 3.6/4.5/8.0 μm

24 μm

Class I CH_3OH masers

Class II CH_3OH masers

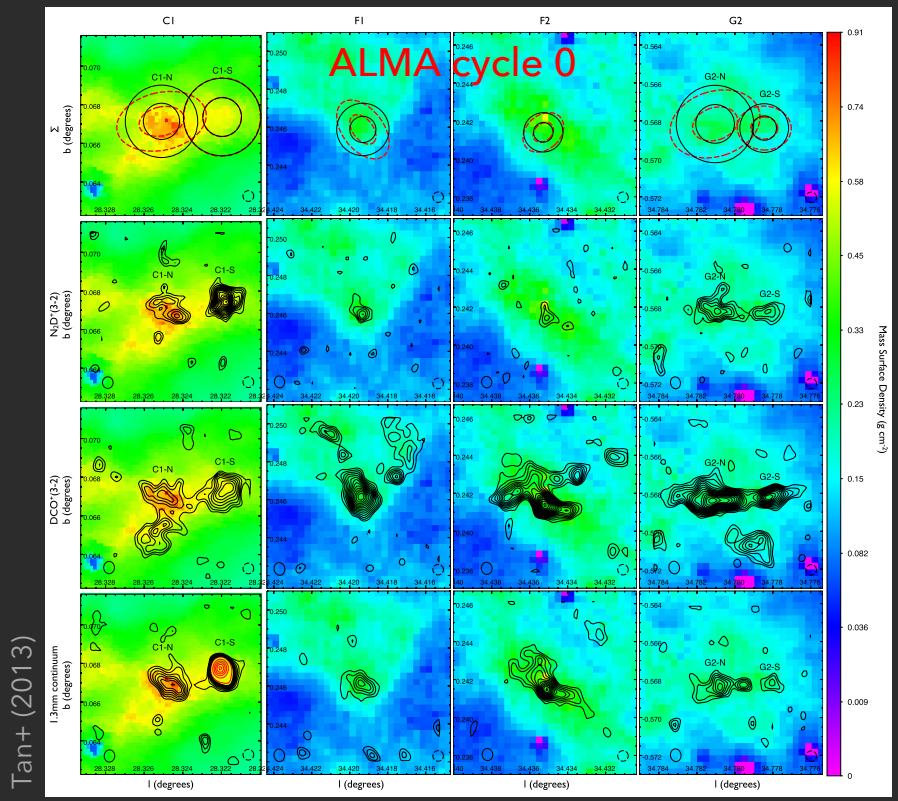


IRDCs: pre-stellar cores?

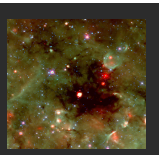
- Starless candidates with large surveys MSX, Spitzer → Herschel: IR-quiet at 24 or 70 μm and T < 15 K (Beltrán+ 2006; Motte+ 2007; Chambers+ 2009; Rathborne+ 2010; Butler & Tan 2012; Traficante+ 2015; Svoboda+ 2016; Tigé+ 2017)

⚠ Too low densities (diffuse structures) (e.g. Peretto+ 2014) or too low masses when observed at high-angular resolution (e.g., Tan + 2013; Sanhueza+ 2017).

G28-C1 G34-F1 G34-F2 G34-G2



Tan+ (2013)



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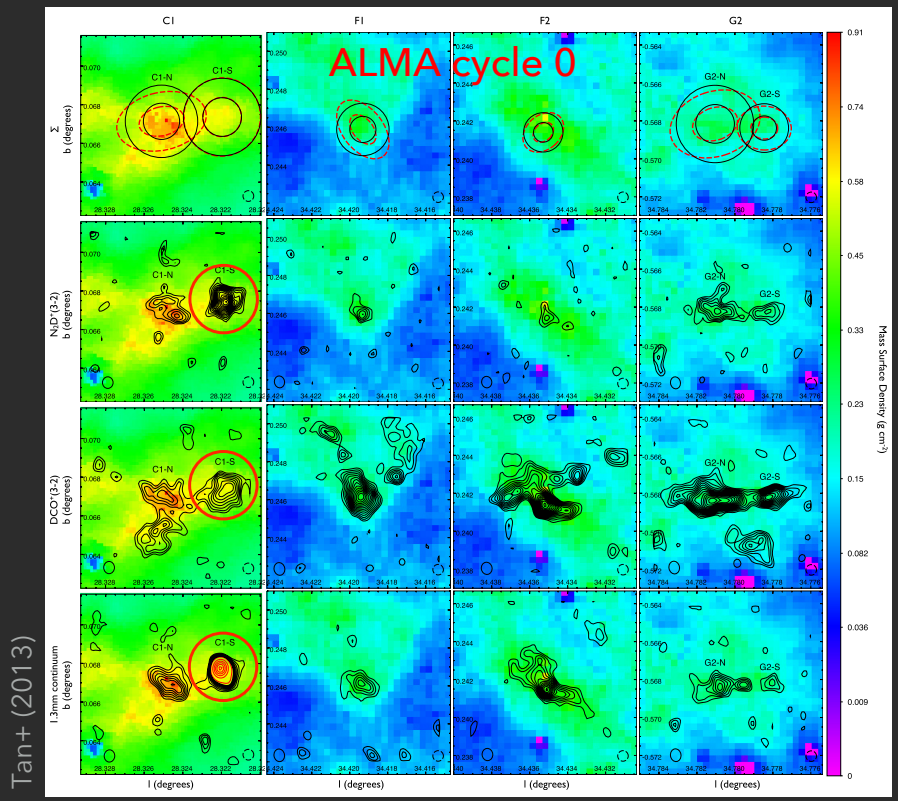

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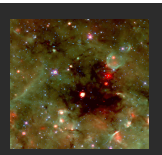

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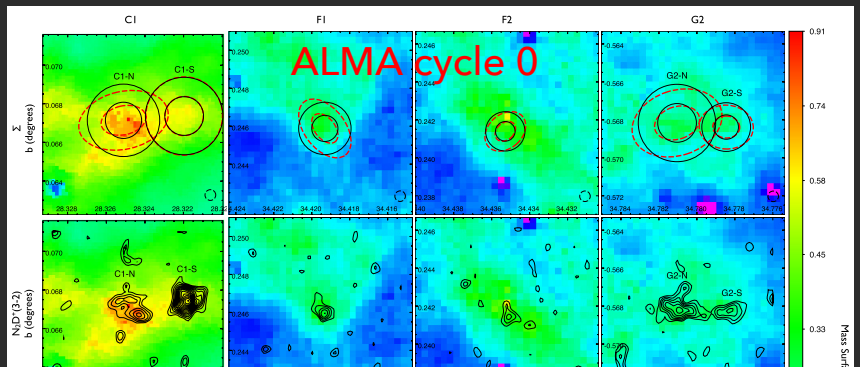
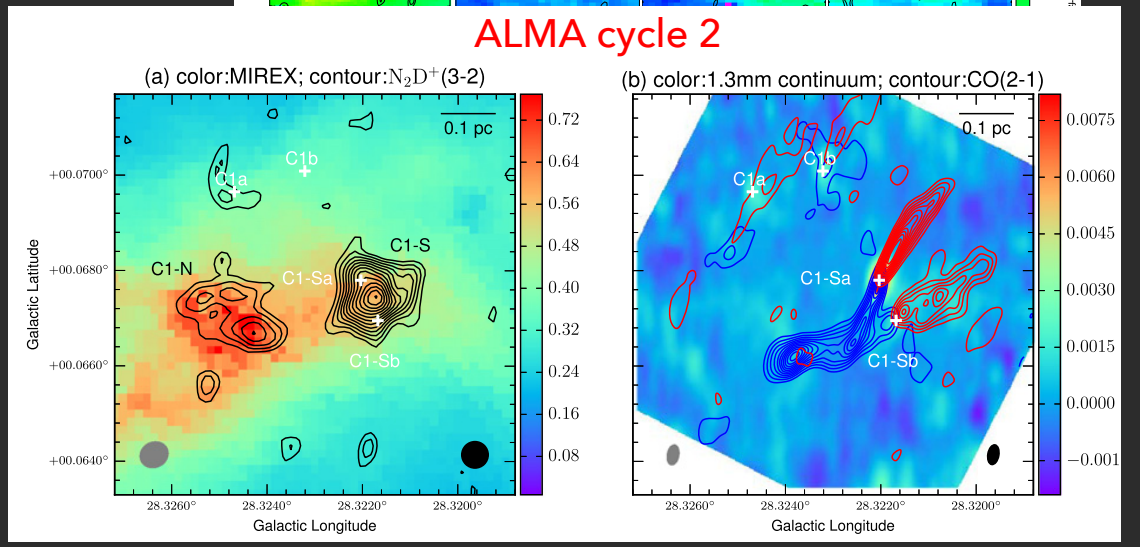
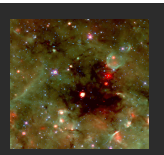
⚠ Massive pre-stellar cores if do exist are very rare (G11P6-SMA: Wang+ 2014 ????).

G28-C1 G34-F1 G34-F2 G34-G2



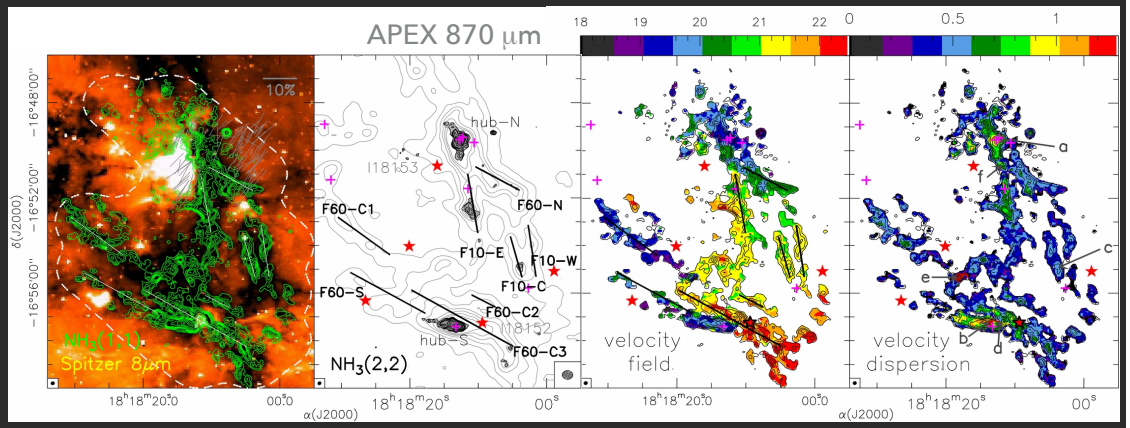




IRDCs: dynamics

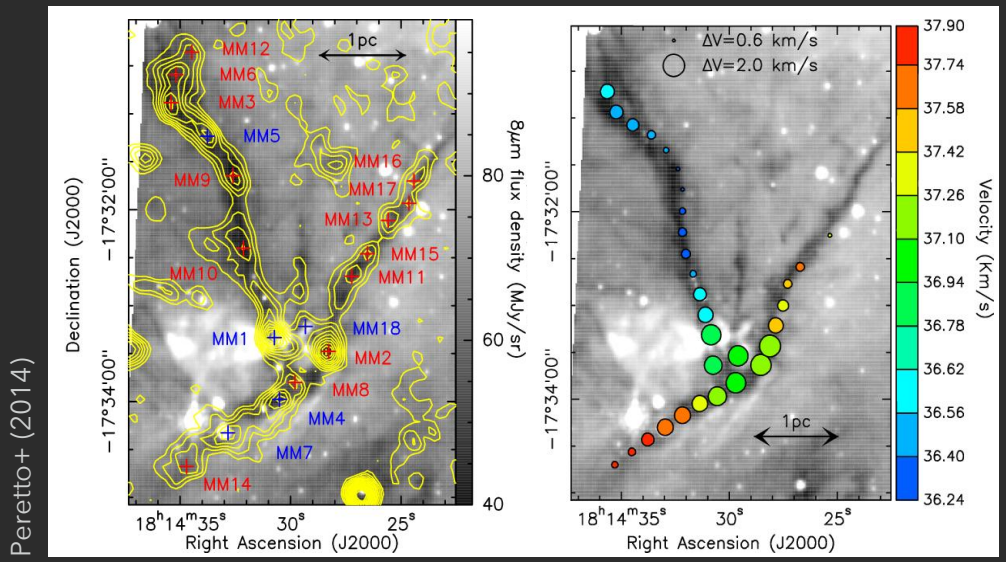
- Network of filaments intersecting in high-density hubs (Myers+ 2009; Liu+ 2012), where compact cores are found.
- Formation of filaments: large-scale turbulence (Arzoumanian+ 2011); convergence of flows or filament-filament collisions (e.g., Heitsch+ 2008; Jiménez-Serra+ 2010; Schneider+ 2010; Henshaw+ 2013; Miettinen 2012); Nakamura+ 2012); magnetic fields (e.g., Nagai+ 1998; Nakamura & Li 2008).
- Filaments present either subsonic or supersonic non-thermal motions (e.g. Hacar & Tafalla 2011; Pineda+ 2011; Csengeri+ 2011).
- Coherent velocity along the filaments (e.g. Jackson+ 2010; Busquet+ 2010) that suggests longitudinal collapse (e.g. Peretto+ 2014) towards the center of the system.
- Velocity dispersion increases in the hubs, which is where star formation occurs.

G14.225−0.506

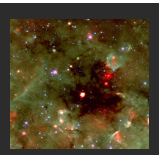


Busquet+ (2013)

SDC13

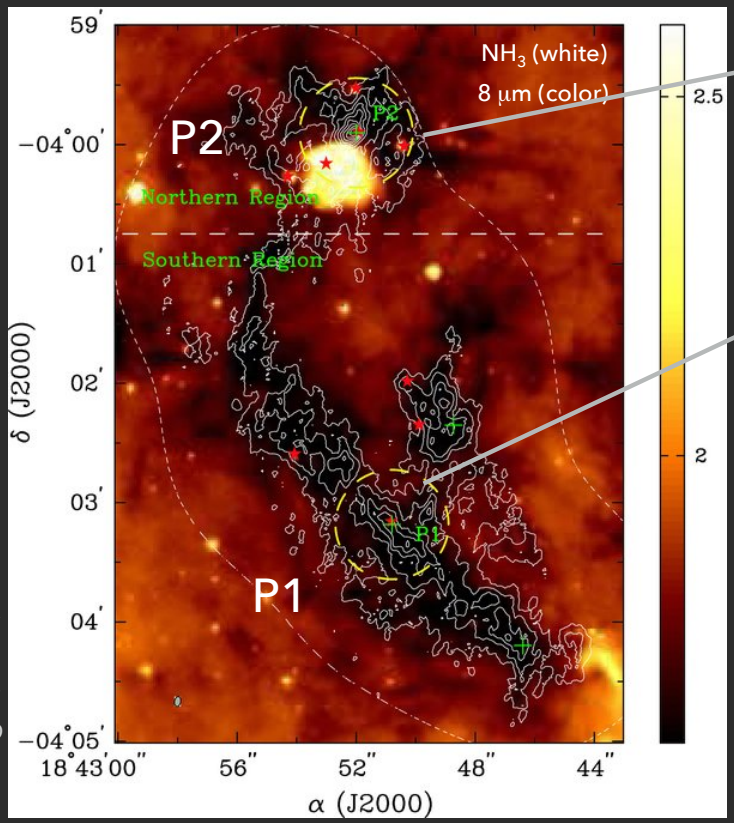


Peretto+ (2014)



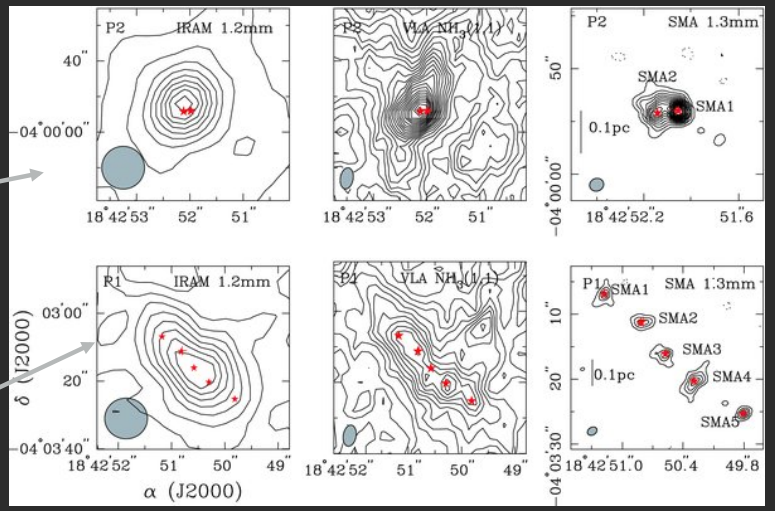
IRDCs: fragmentation

G28.24+0.06

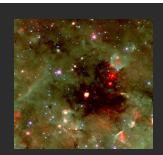


Zhang+ (2009)

SMA



- Some IRDCs fragment in many cores and some in few. Limited fragmentation (Bontemps+ 2010; Longmore+ 2011; Palau+ 2013), or highly fragmented structures (Zhang+ 2015; Rathborne +2015; Palau+ 2017; Henshaw et al. 2017).



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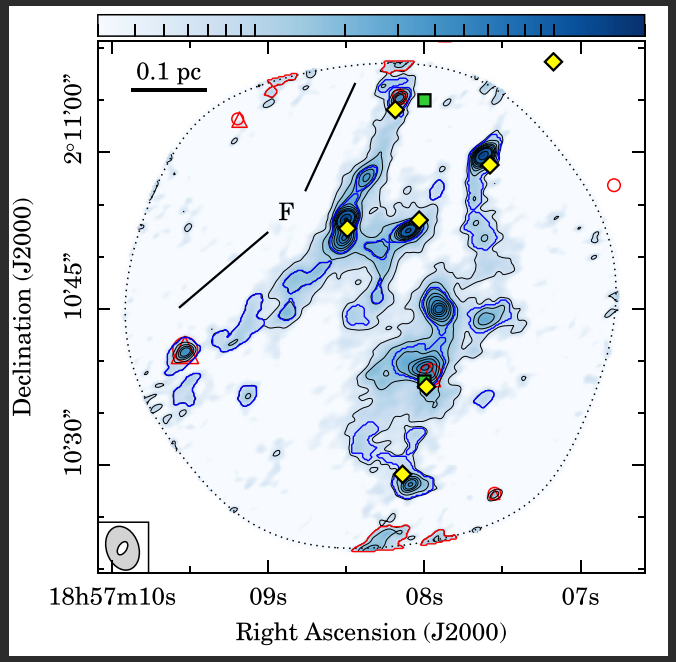
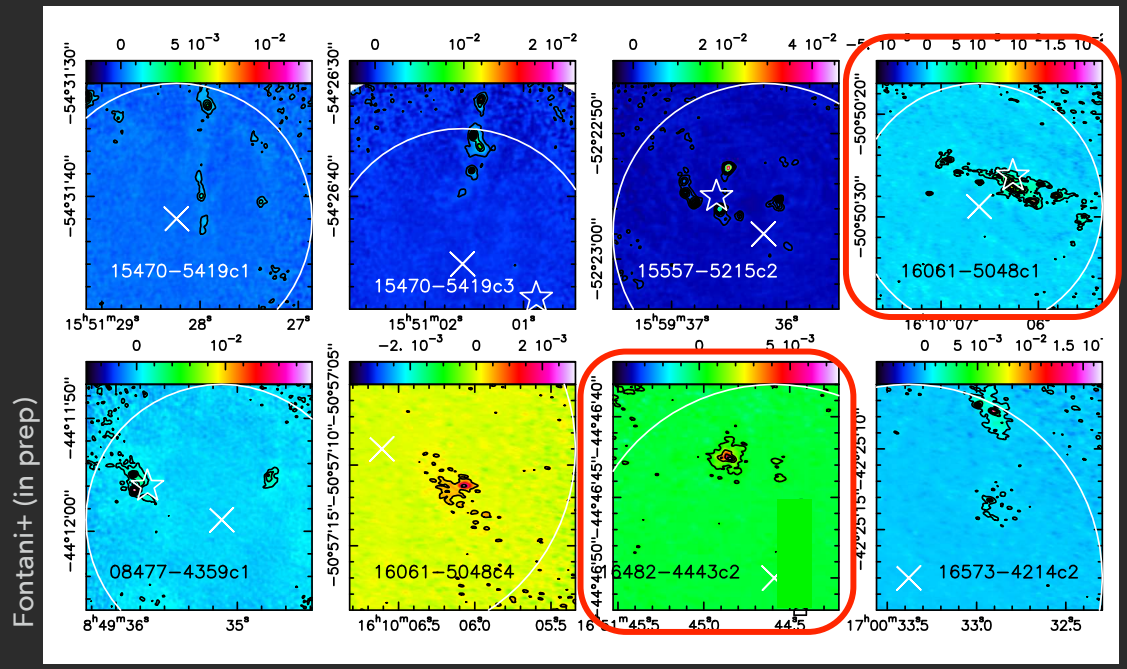


Henshaw+ (2017)

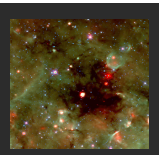
ALMA



Fontani+ (in prep)

- Some IRDCs fragment in many cores and some in few. Limited fragmentation (Bontemps+ 2010; Longmore+ 2011; Palau+ 2013), or highly fragmented structures (Zhang+ 2015; Rathborne +2015; Palau+ 2017; Henshaw et al. 2017).

- IRDCs fragments have masses up to few tens of $M_{\odot}$ → super-Jeans masses ➔ cloud fragmentation may not be controlled solely by the thermal pressure and gravity ➔ turbulence/magnetic field??



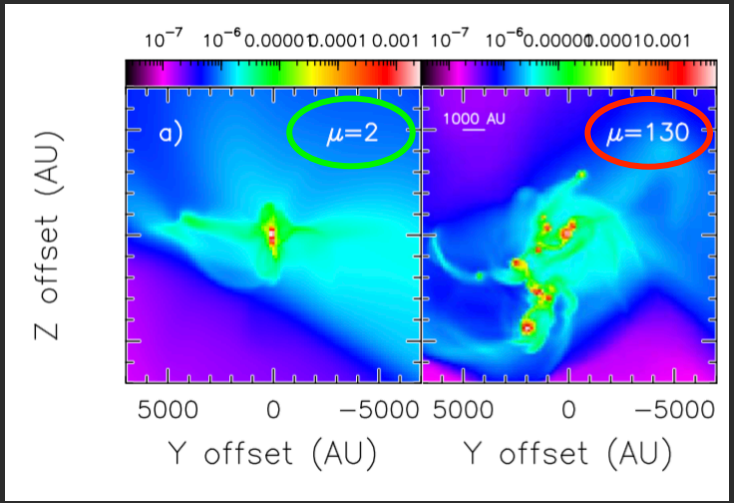
IRDCs: fragmentation

- 3D Radiation-magneto-hydrodynamics simulations show that magnetic field and radiative transfer strongly interplay at the early stages of star formation (Hennebelle+ 2011; Commerçon+ 2011, 2012).
- The magnetic intensity is set by μ = (M/ M/Φ)/ (M/Φ)crit), the value of mass-to-flux over critical mass-to-flux ratio
- If magnetic field dominates (low μ) → one (few) fragments.
- If turbulence dominates (high μ) → many fragments

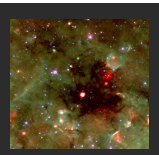
$$\mu = (M/\Phi)/(M/\Phi)_{crit}$$

μ = 2 , dominant magnetic support

μ = 130, faint magnetic support



Model output (Hennebelle+ 2011; Commerçon+ 2012)



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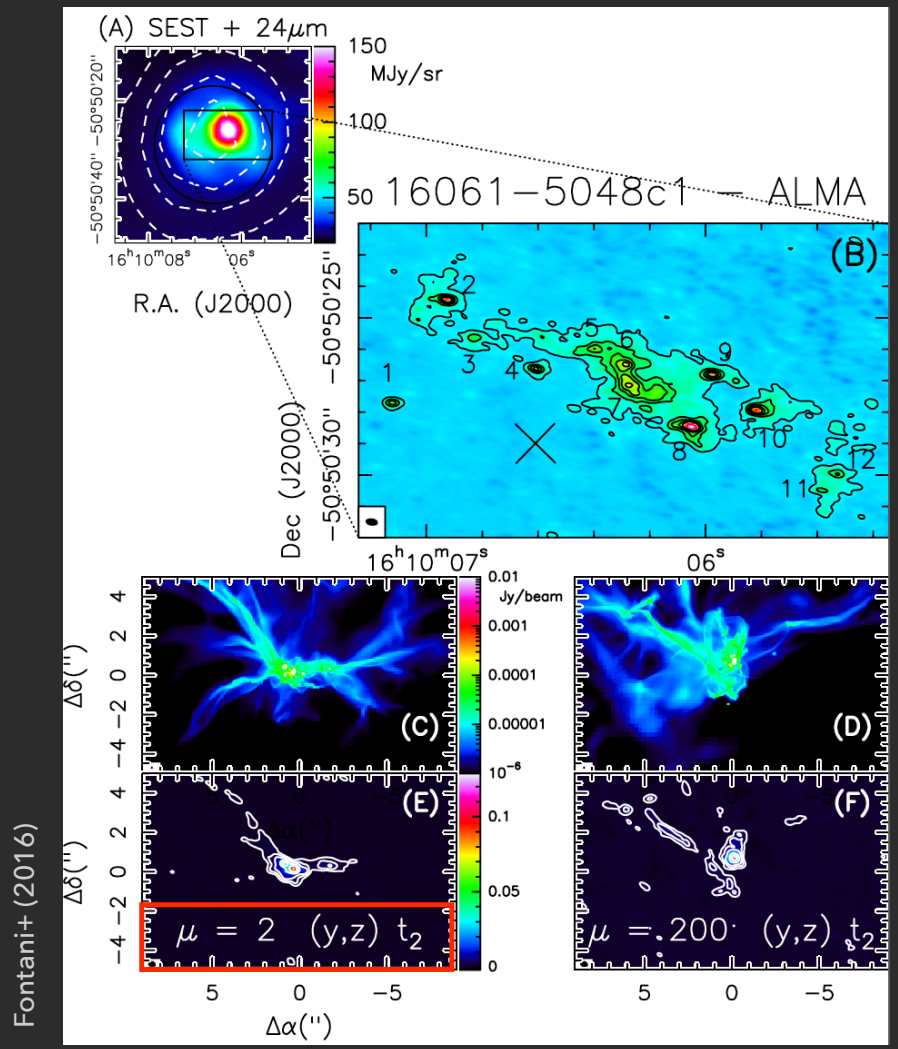
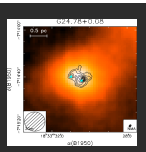


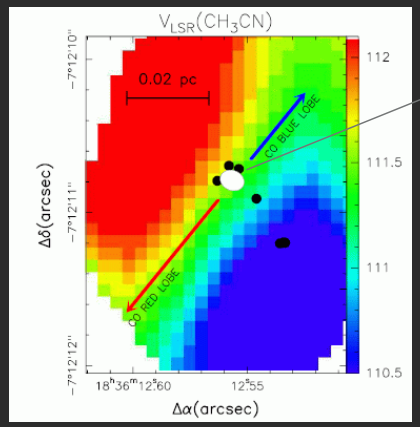
Despite many fragments, overall morphology in line with strong magnetic support (μ=2) → magnetic field plays a dominant role in the fragmentation process



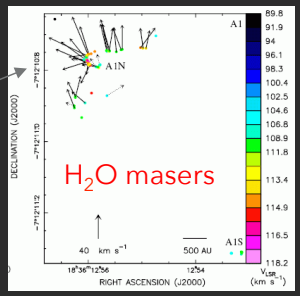
Hot Molecular Cores

- HMCs are the cradles of OB protostars.
- Sometimes are associated with HC/UC HII regions
- Properties:
  - sizes 0.1 pc
  - T > 100 K
  - n~10^7 cm^{-3}
  - L > 10^4 $L_\odot$
- Rich chemistry: evaporation of dust grain mantles

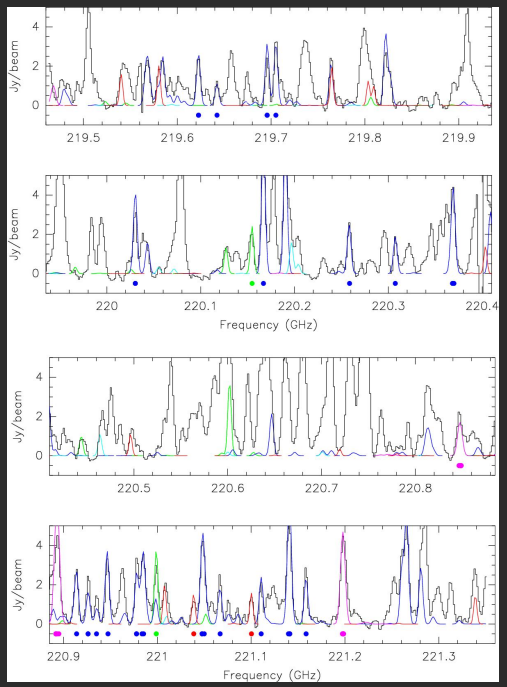
G24.78+0.08 A1



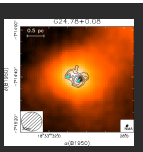
Moscadelli+ (2007)



G31.41+0.31

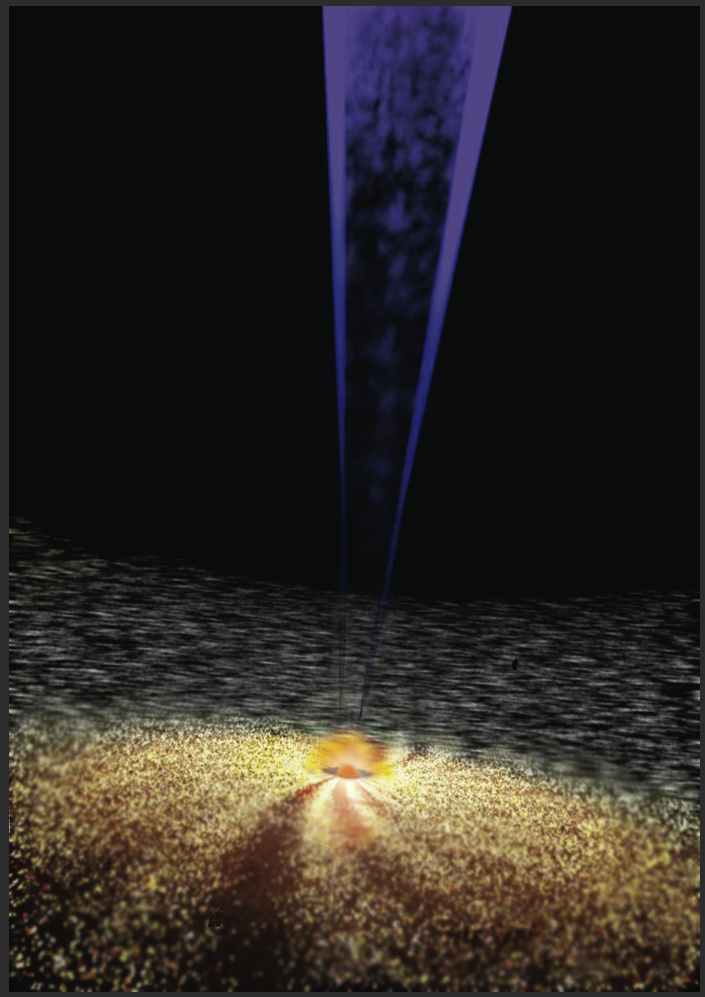


Rivilla+ (2017)

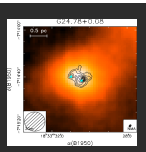


HMCs: Accretion disks?

- High-mass star-forming theories appear to converge to a disk-mediated accretion scenario (McKee & Tan 2002; Krumholz+ 2009; Bonnell & Bate 2006; Keto 2007) but ...
- ... what do the observations tell us?

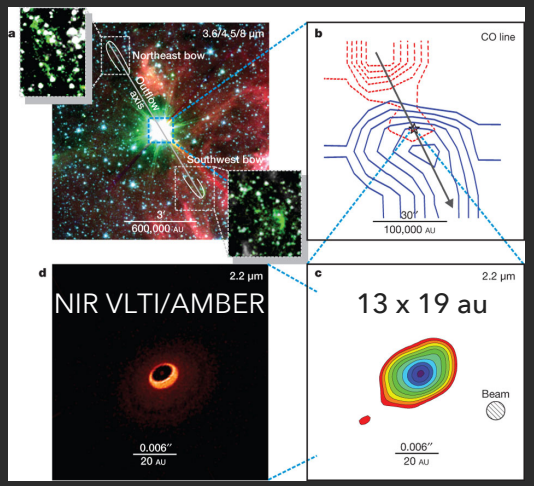


© Carbonaro



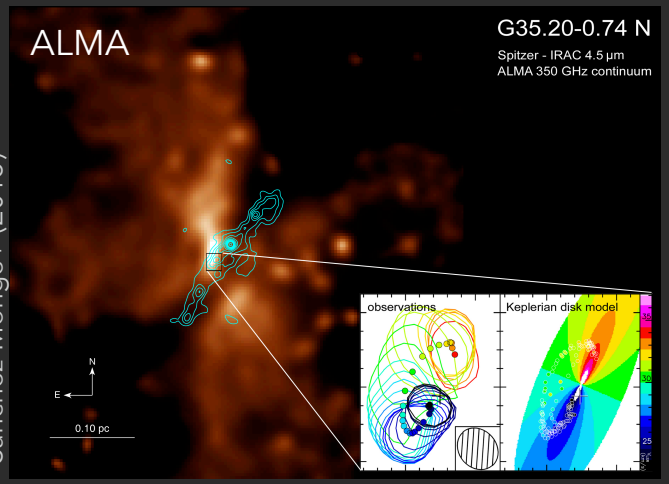
B-type to late O-type stars: $L_{bol} < 10^5\ L_\odot \Rightarrow M_\star \lesssim 25\ M_\odot$

IRAS 13481-6214 : ~20 $M_\odot$



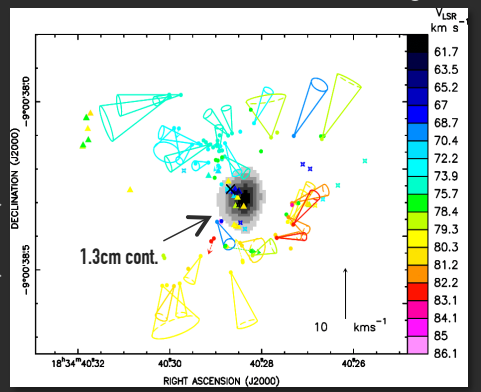
Kraus+ (2010)

G35.20-0.74N: ~18 $M_\odot$



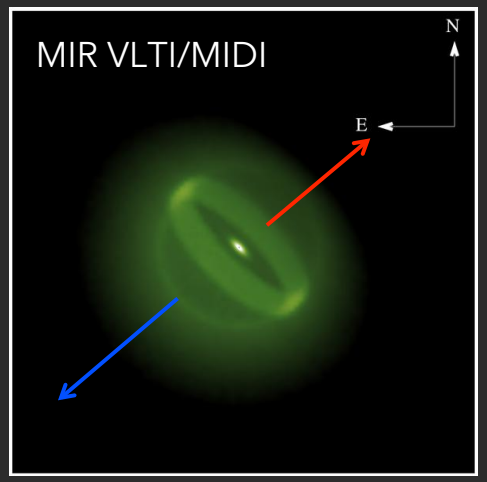
Sánchez-Monge+ (2013)

G23.01-0.41: ~20 $M_\odot$



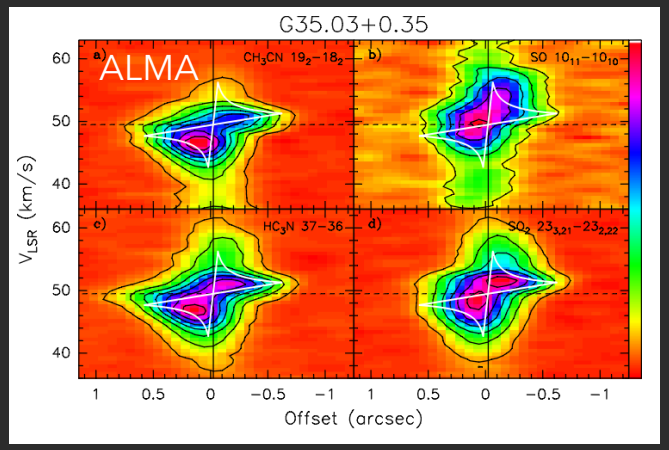
Sanna+ (2010)

CRL 2136: ~20 $M_\odot$



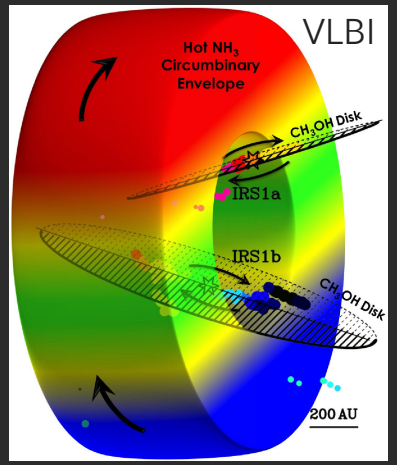
de Wit+ (2011)

G35.03-0.35: ~10 $M_\odot$

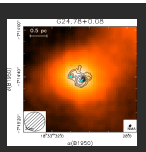


Beltrán+ (2014)

NGC 7538 IRS1: ~25 $M_\odot$



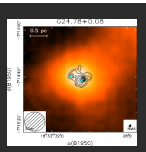
Moscadelli & Goddi (2014); Goddi+ (2015)



B-type to late O-type stars: $L_{bol} < 10^5\ L_\odot$ ➪ $M_\star \lesssim 25\ M_\odot$

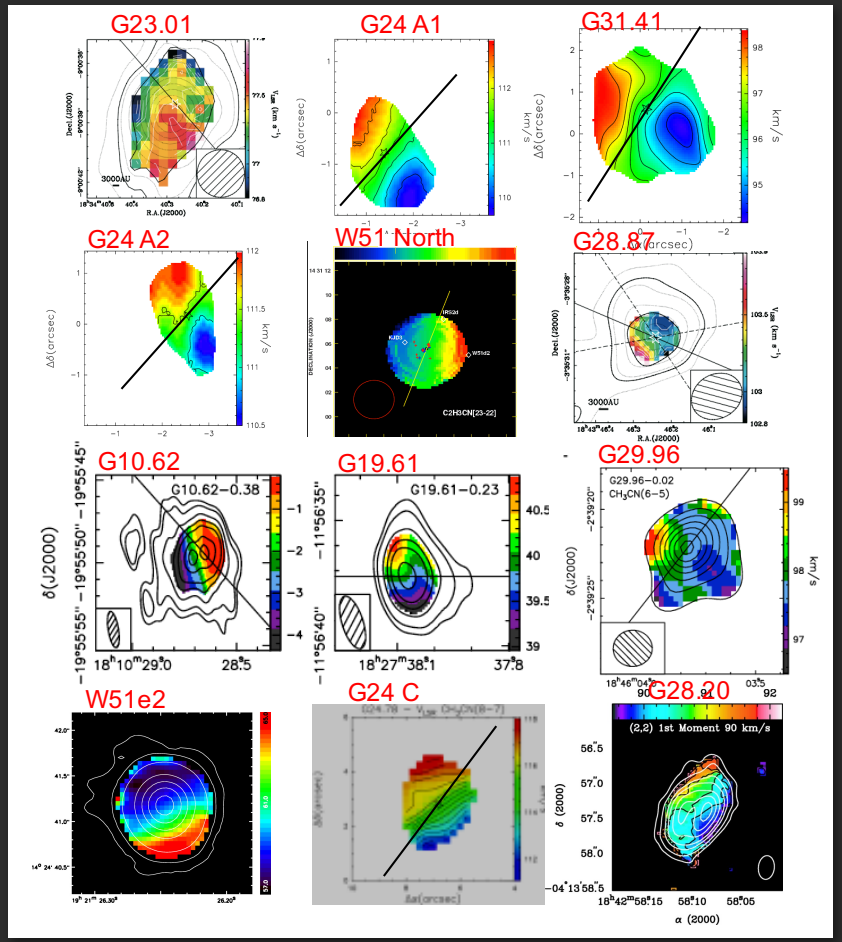
- Many more: Cepheus A HW2 (Patel+ 2005; Torstensson+ 2011); G23.657-0.127: (Bartkiewicz+ 2005, 2016); AFGL 2591 VLA3 (Wang et al. 2012); IRAS 20126+4104 (Cesaroni et al. 2014); AFGL 4176 (Johnston+ 2015); G351.77-0.54 (Beuther+ 2017); G23.01-0.41 (A. Sanna) …

- $L_{bol} < 10^5\ L_\odot$ ➪ $M_\star$ = 7-25 $M_\odot$
- R_{disk} a few 100 - 10^3 au
- M_{disk} ~ a few $M_\odot$ ➪ $M_{disk} \lesssim M_\star$

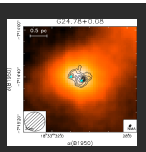


Early O-type stars: $L_{bol} > 10^5\ L_\odot$ ➪ $M_\star > 25\ M_\odot$

- R_{toroid} several 1000 au
- M_{toroid} ~ a few 100 $M_\odot$ ➪ $M_{toroid} \gg M_\star$
- $M_{toroid} >> M_\star$: No Keplerian rotation on scales of 10^4 au. The gravitational potential of the system is dominated by the massive toroid not by central star.
- $M_{toroid} > M_{dyn}$ suggests that toroids are not centrifugally supported, may be unstable and undergoing fragmentation and collapse.



Beltrán+ (2004, 2011), Furuya+(2008), Keto & Klaassen (2008), Sollins + (2005), Zapata+(2008)



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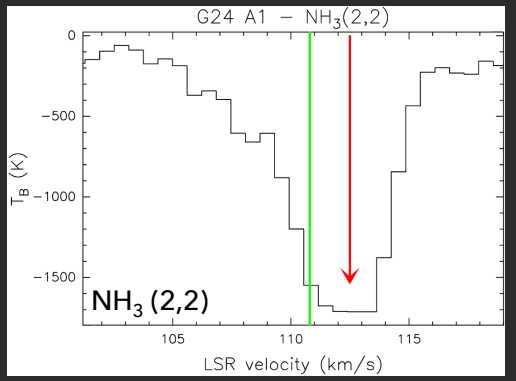
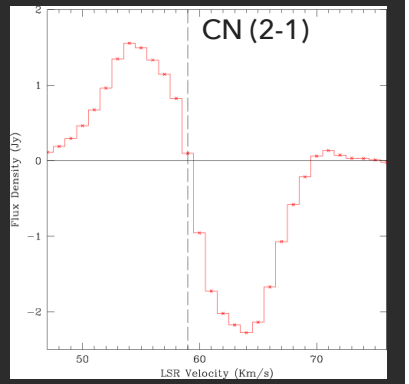
- $M_{toroid} > M_{dyn}$ suggests that toroids are not centrifugally supported, may be unstable and undergoing fragmentation and collapse.
- Inverse P-Cygni profiles (or red-shifted absorption) towards bright embedded sources have been detected:
  - ❑ hypercompact HII regions (very bright at cm λ's) as for G10.62 (Keto+ 1988; Sollins 2005), W51e2 (Zhang & Ho 1997), G24.78 A1 (Beltrán+ 2006), G20.08-0.14N (Galván-Madrid+ 2009)
  - ❑ a strong compact millimeter source as for W51 North (Zapata+ 2008), G31.41+0.31 (Girart+ 2009), G19.61-0.23 (Wu+ 2009), NGC7538IRS1 (Beuther + 2013)

G24.78+0.08 A1



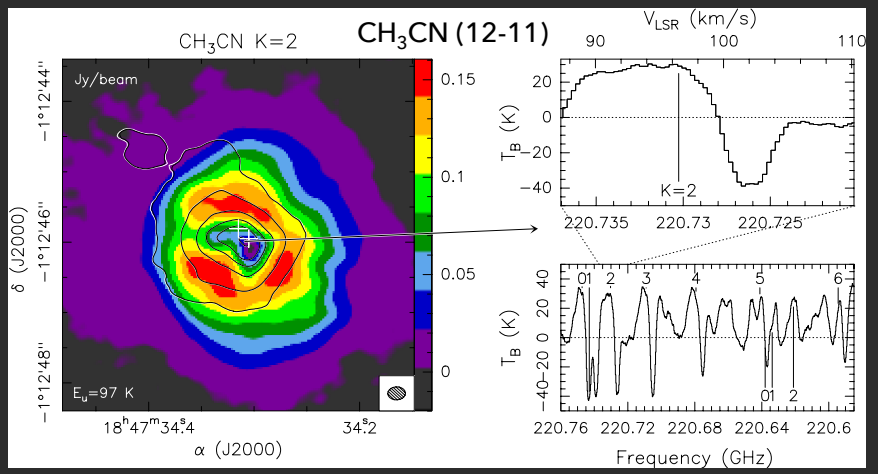
Beltrán+ (2006)

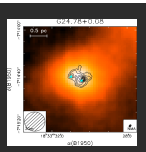
W51 North



Zapata+(2008)

G31.41+0.31



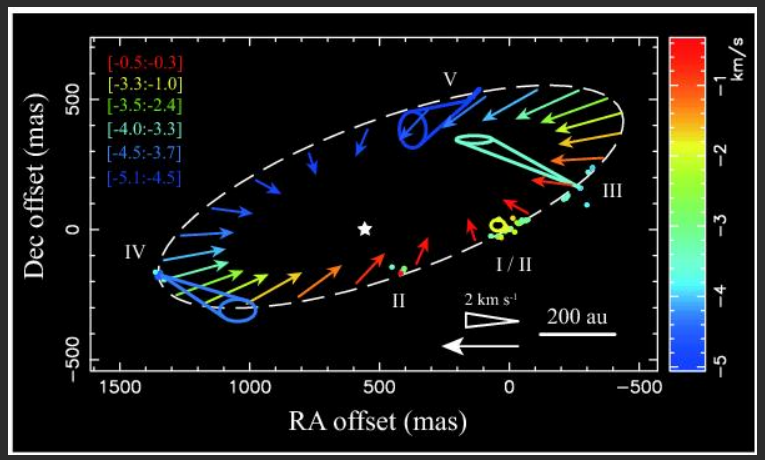


Early O-type stars: $L_{bol} > 10^5\ L_\odot$ ➪ $M_\star > 25\ M_\odot$

CN (2-1)

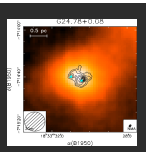
- R_{toroid} several 1000 au
- M_{toroid} ~ a few 100 $M_\odot$ ➪ $M_{toroid} \gg M_\star$
- $M_{toroid} >> M_\star$: No Keplerian rotation on scales of 10^4 au. The gravitational potential of the system is dominated by the massive toroid not by central star.
- $M_{toroid} > M_{dyn}$ suggests that toroids are not centrifugally supported, may be unstable and undergoing fragmentation and collapse.
- Inverse P-Cygni profiles (or red-shifted absorption) towards bright embedded sources have been detected
- Methanol maser proper motions

Cepheus A-HW2



Sugiyama+ (2014)

Recently confirmed by Sanna+ (2017)

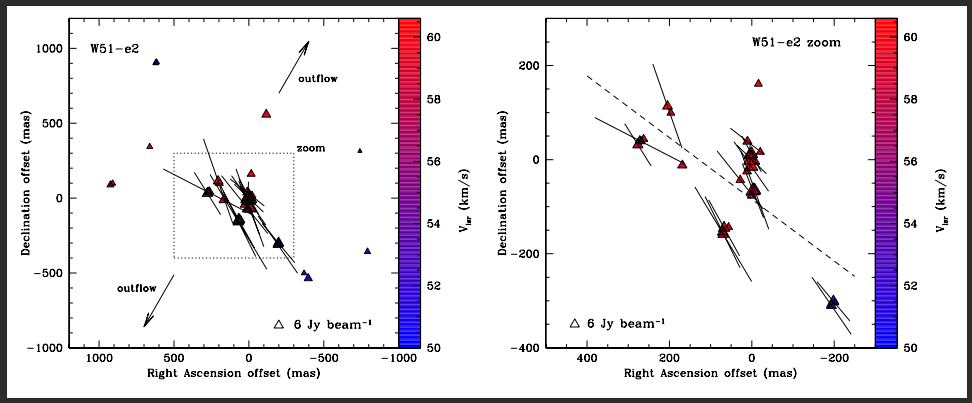


Early O-type stars: $L_{bol} > 10^5\ L_\odot$ ➪ $M_\star > 25\ M_\odot$

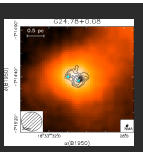
Are disks embedded in the toroids?

- Typical d = 5 kpc → angular resolution better than 0.2" to trace < 1000 au
- Up to cycle 2 of ALMA, VLBI observations of maser emission were the only ones tracing R<1000 au (Surcis+ 2012)
- W51e2 -E ($1.5\times10^6\ L_\odot$) show CH_3OH at <1000 au → keplerian disk?
- ⚠ In some cases, proper motions of CH_3OH indicate expansion instead of rotation (e.g. Li + 2012; Moscadelli+ 2013)

W51e2 -E



Surcis+ (2012)



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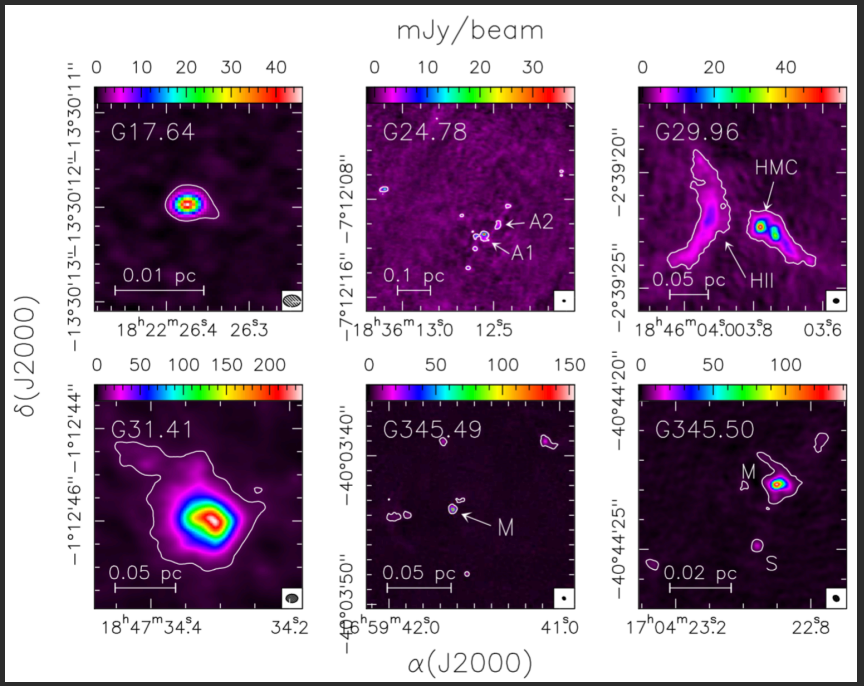
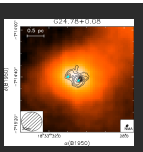


Cesaroni+ (2017)

0.2″ ALMA

(400 au – 1600 au resolution)



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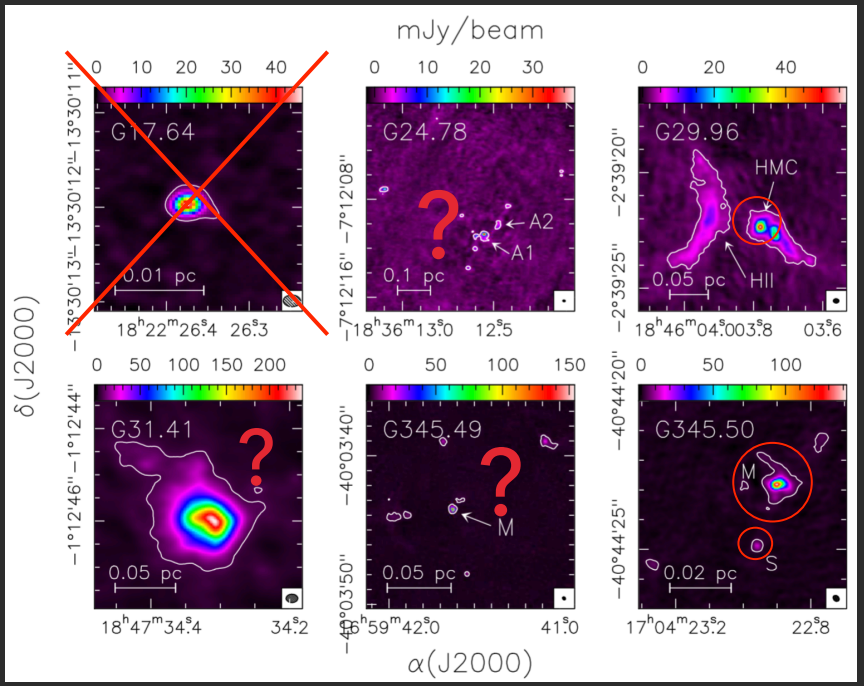
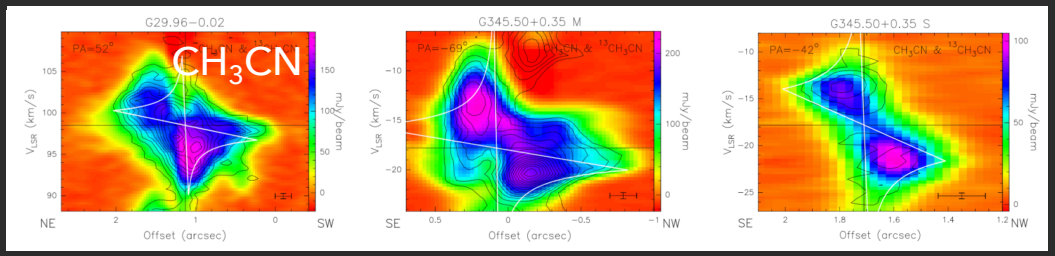


Cesaroni+ (2017)

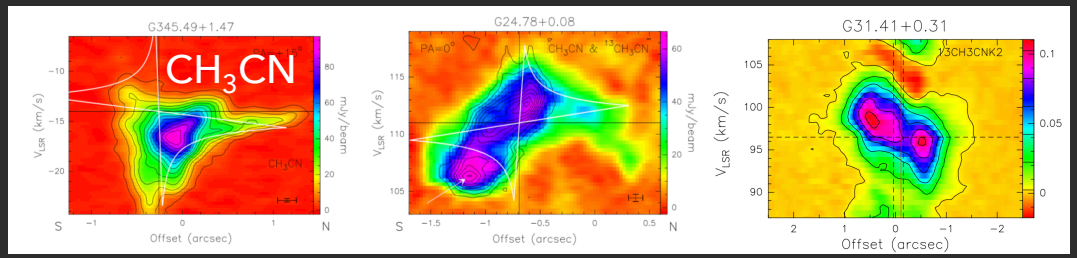
0.2″ ALMA

(400 au – 1600 au resolution)

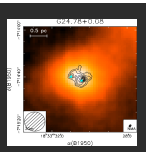
Keplerian-like rotation



Rotation, but Keplerian?



Cesaroni+ (2017)



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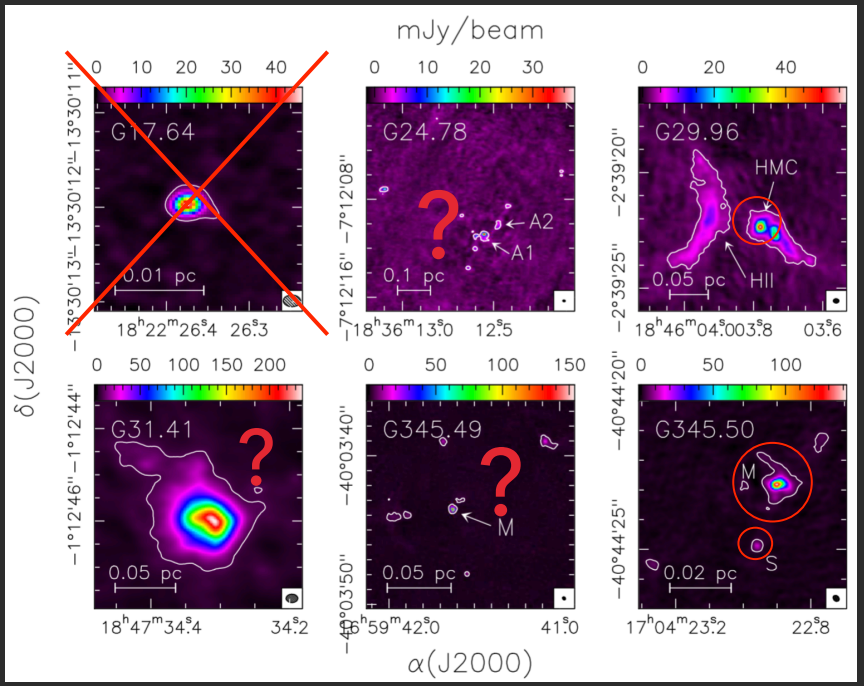

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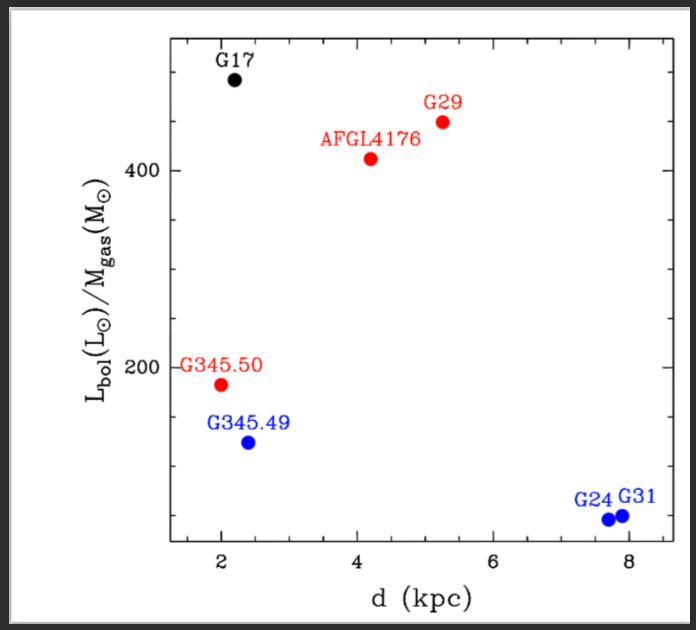
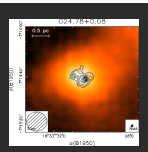


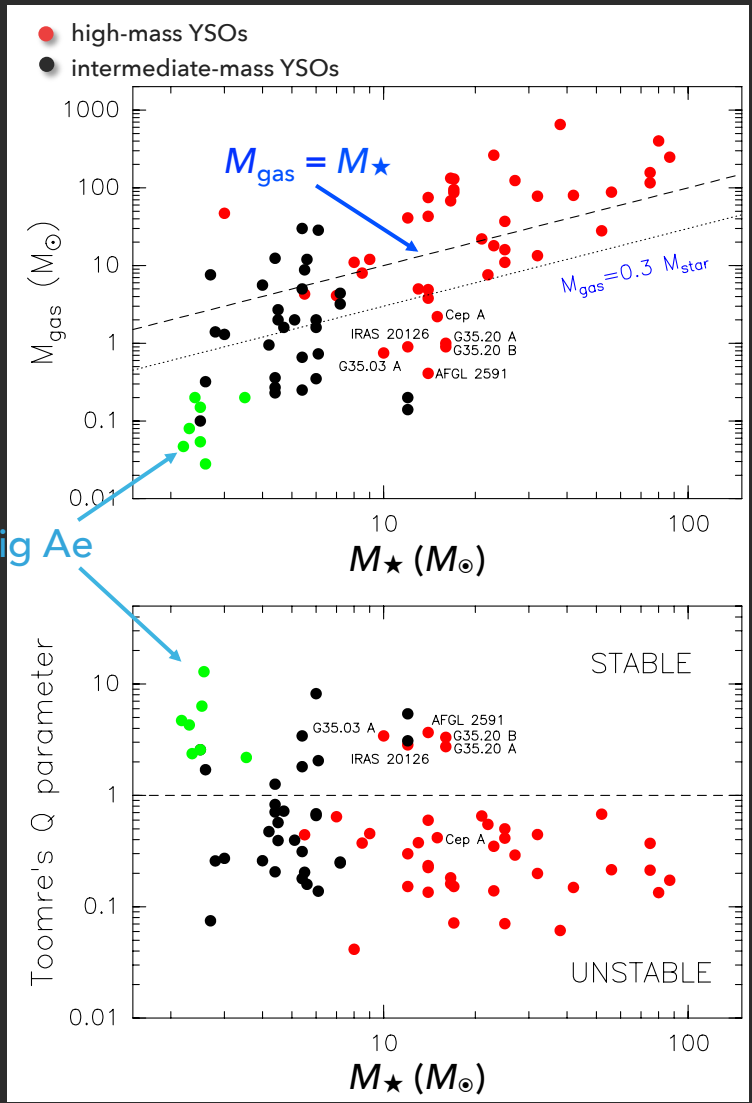
Cesaroni+ (2017)

- Disks found at intermediate evolutionary stage
- At later evolutionary stage, the molecular gas is dispersed
- For the younger sources, emission of disks difficult to disentangle from that of the envelopes. Disks might start small and grow up with time

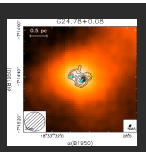


STABILITY

- 41 rotating structures around O and B-type
- 30 rotating structures around IMs
- $M_{disk} < 0.3\ M_{\star}$ and Toomre's stability parameter Q > 1 ➜ accretion disks are gravitationally stable (Shu+ 1990; Laughlin & Bodenheimer 1994; Yorke 1995; Toomre 1964)
- Herbig Ae + IRAS 20126+4104 (Cesaroni+ 2005), Cepheus A HW2 (Patel+ 2005), G35.20-0.74N (Sánchez-Monge+ 2013), G35.03+0.35 (Beltrán+ 2014), AFGL 2591 VLA3 (Wang+ 2012) accretion disks are stable against collapse
- Toroids are unstable against axisymmetric instabilities



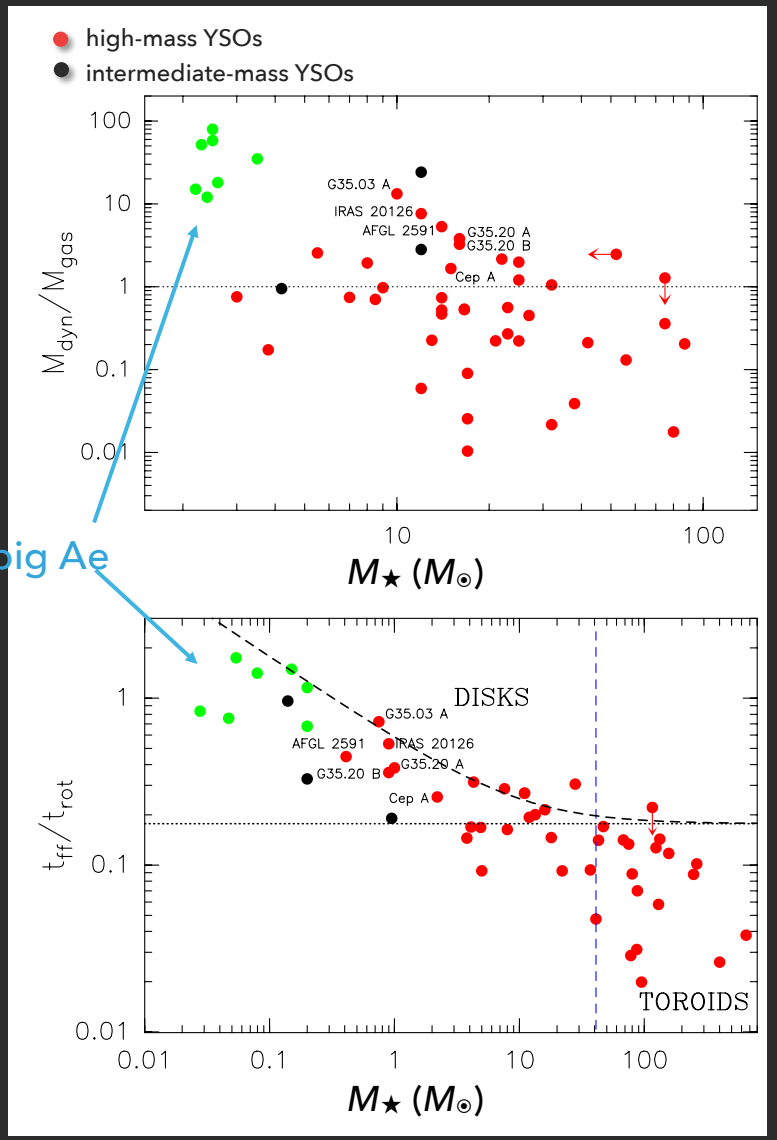
Beltrán & de Wit (2016)



DYNAMICS

- Toroids (M_{gas} >> $M_\star$) and disks are also dynamically different
- $M_\star$< 25 $M_\odot$ + bona fide B-type Keplerian disks: M_{dyn}/M_{gas} > 1 ➔ centrifugally supported
- $M_\star$> 25-30 $M_\odot$ ➔ M_{dyn}/M_{gas} << 1
- Toroids could never reach equilibrium and be transient entities with timescales of the order of t_{ff} ~10^4 yr

- If structure rotates fast and t_{ff}/t_{rot} high ➔ infalling material that incorporates into the fast rotating structure has enough time to settle into a centrifugally supported disk
- If structure rotates slowly and t_{ff}/t_{rot} low ➔ infalling material does not have enough time to reach centrifugal equilibrium and the rotating structure is a transient toroid (rotation plays no role in their support)



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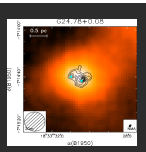
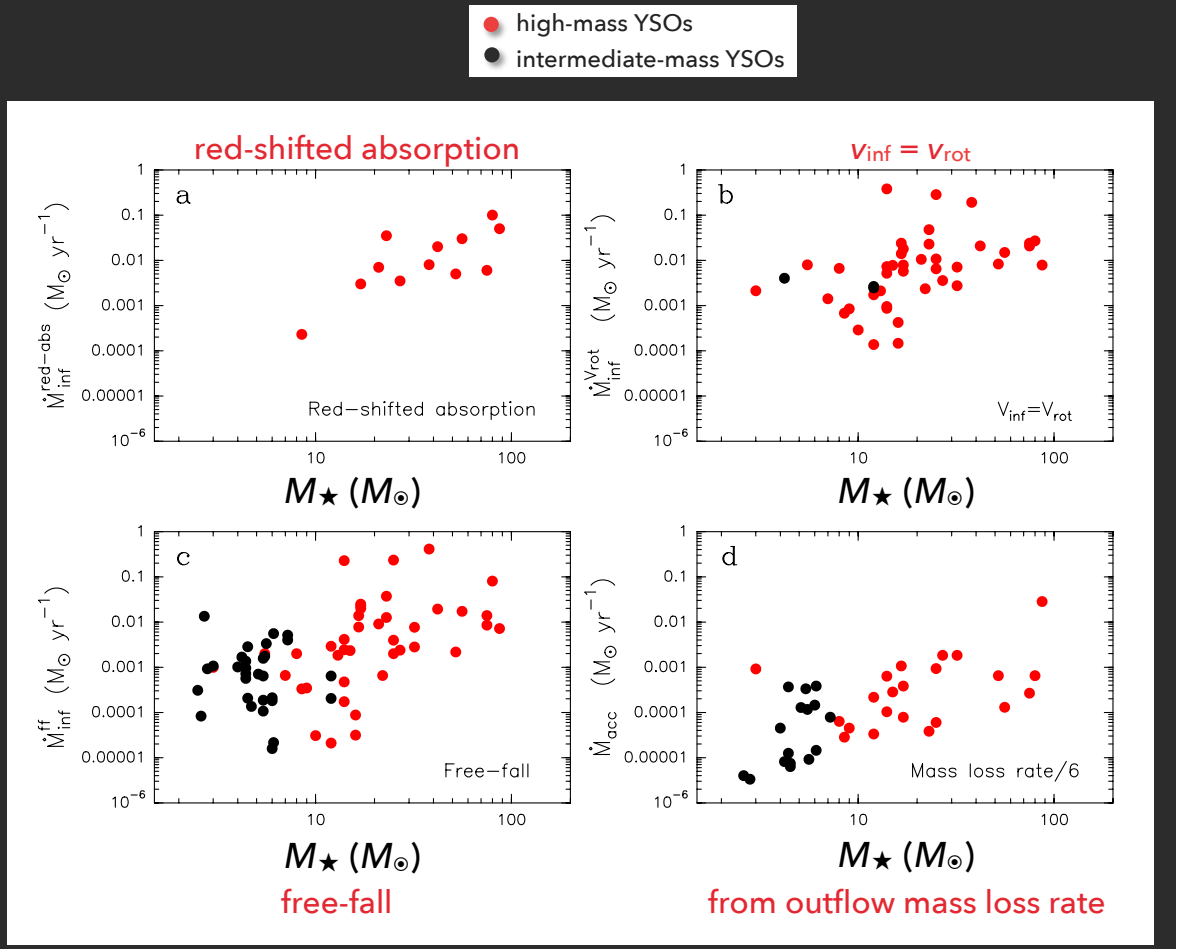
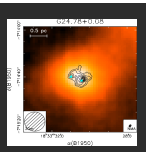


INFALL VS. ACCRETION

1. Red-shifted absorption
2. v_{inf}=v_{rot}
3. Free-fall → $\dot{M}_{inf} = M_{gas}\, t_{ff}$
4. Mass loss rate → $\dot{M}_{out} = 20\, \dot{M}_{jet} = 6\, \dot{M}_{acc}$ (Tomisaka 1998; Shu+ 1999)



Beltrán & de Wit (2016)



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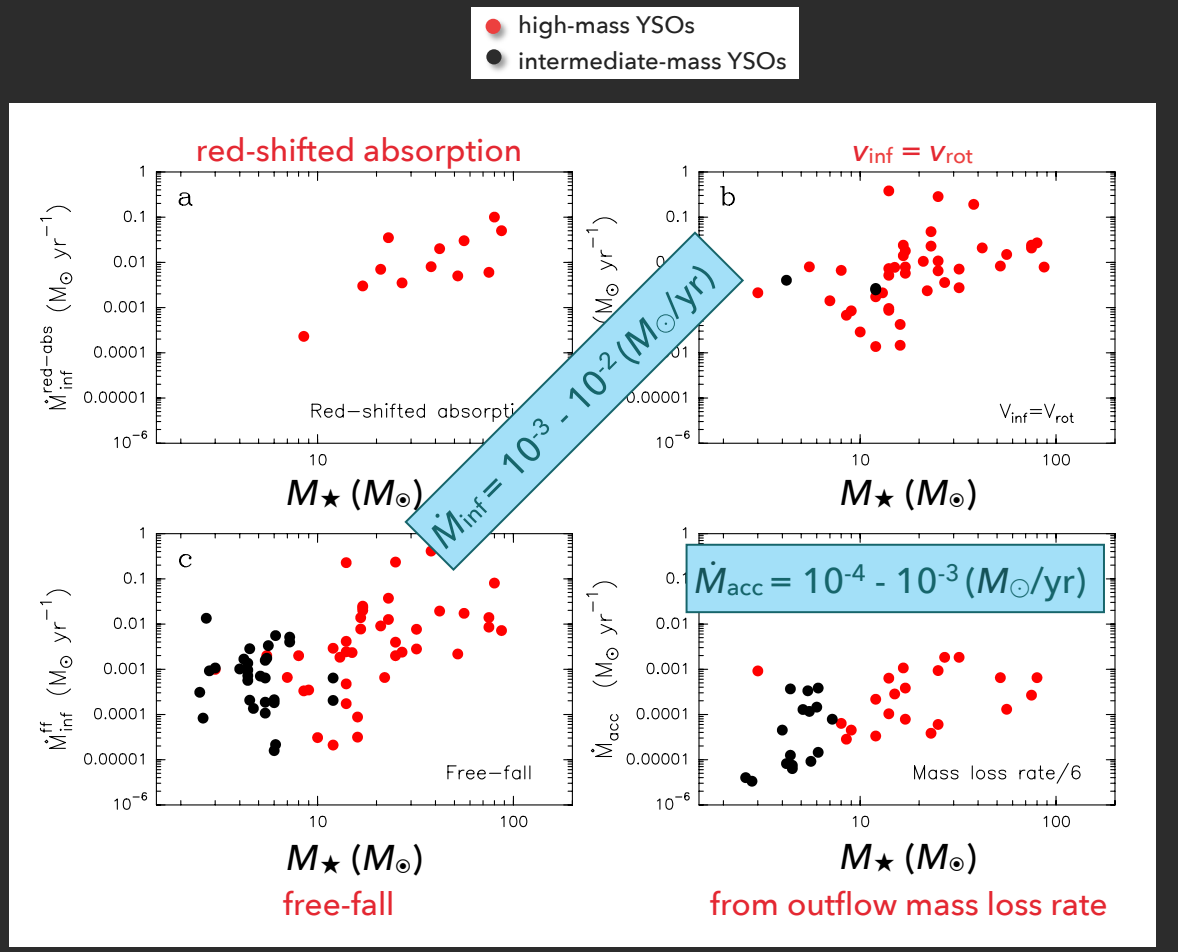
- Infall rate increases with mass of central star
- $\dot{M}_{inf} > \dot{M}_{acc}$ independently of method used



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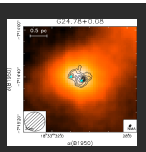
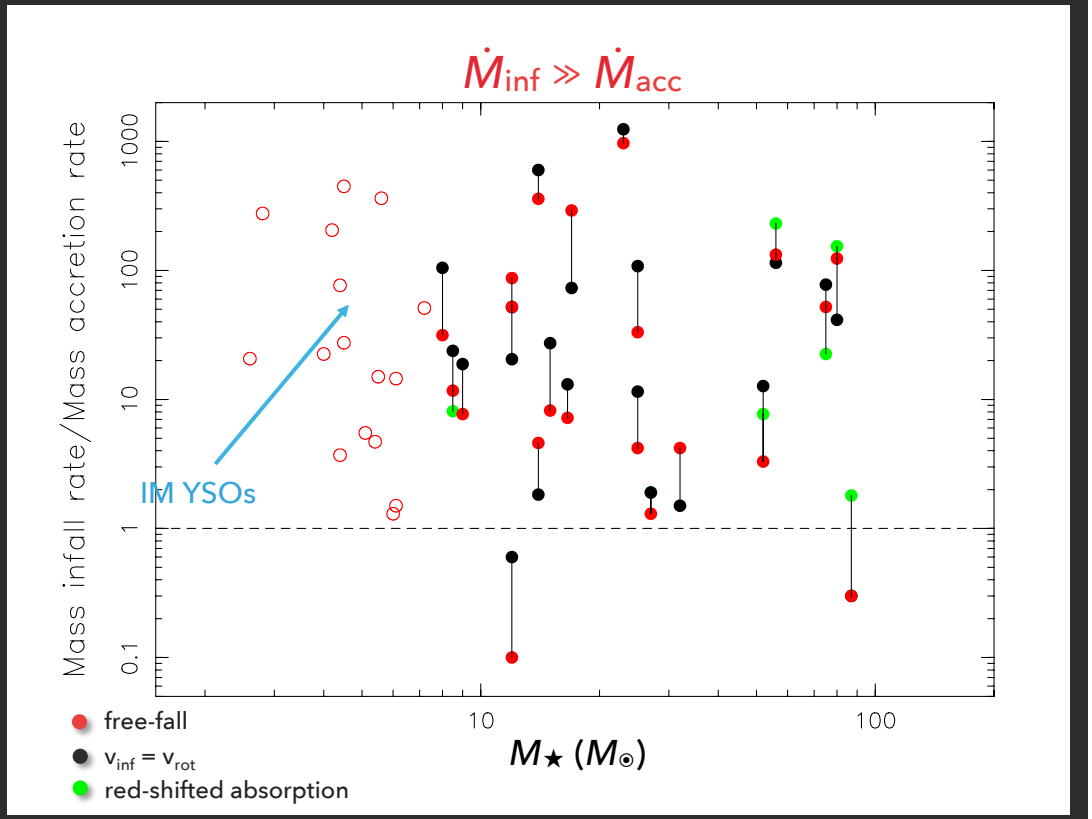


INFALL VS. ACCRETION

- $\dot{M}_{inf} > \dot{M}_{acc}$ independently of method used
- Stellar multiplicity
- Infalling rate onto the disk different from accretion onto star → material piles up and results in disk masses which are tens to hundreds of solar masses. This is massive and suggests a gravitationally unstable disk-inducing variable, "FUOri-like" accretion events onto the central object.



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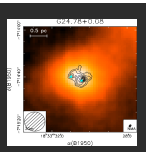


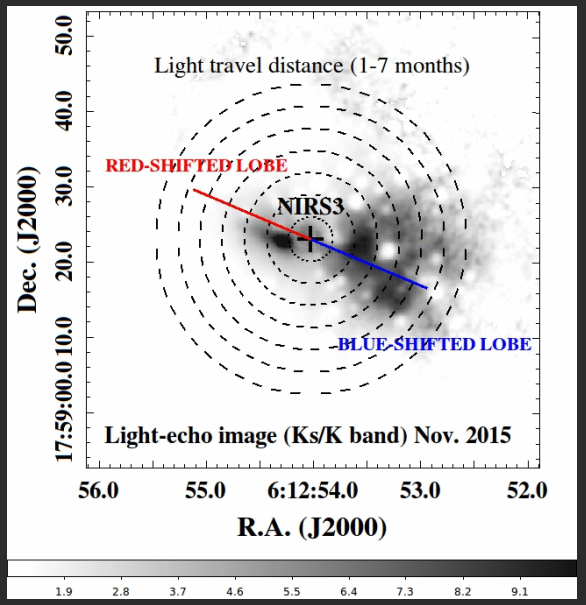
FIRST DISK-MEDIATED ACCRETION BURST FROM A HMYSO

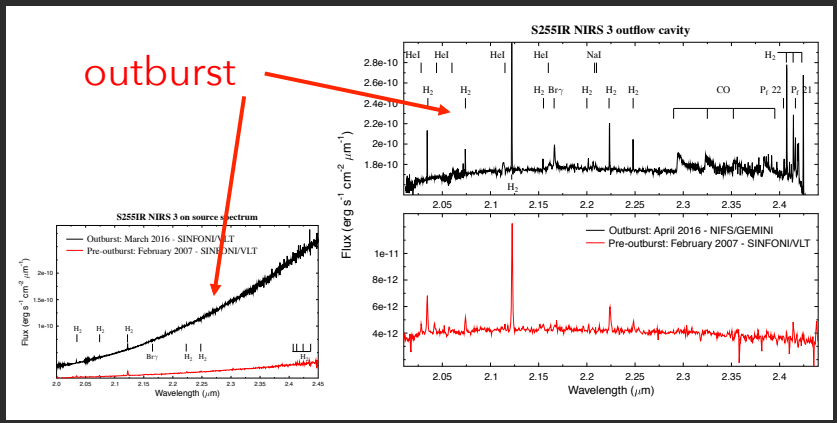
- S255 NIR 3: 2.4 x10^4 $L_\odot$ (~15 $M_\odot$)
- NIR photometry reveals an increase in brightness of 2.5-3.5 magnitudes and NIR spectroscopy reveals emission lines typical of accretion bursts in low-mass protostars, but orders of magnitude more luminous.
- The energy released and the inferred mass-accretion rate are also orders of magnitude larger.
- $\dot{M}_{acc}$ ~ 5 x 10^{-3} $M_\odot$/yr (for 20 $M_\odot$ and 10 $R_\odot$)

➢ See also Kumar+ (2016)

➢ Also NGC 6334I-MMI shows bursts at submm l's (Hunter+ 2017)

S255 NIR 3





Caratti o Garatti+ (2016)

SUMMARY

- All high-mass star-forming theories (turbulent monolithic collapse/competitive accretion) appear to converge to a disk-mediated accretion scenario. Models are converging, but still caveats in both.

- The initial conditions of massive star formation are beginning to be studied in detail: fragmentation in IRDCs, dynamics, star formation activity, evolutionary sequence

    - Massive pre-stellar cores if do exist are very rare as all IRDCs appear to be associated with star-formation activity

    - Simulations propose that magnetic field plays a dominant role in the fragmentation process of IRDCs, but magnetic field observations (polarization, Zeeman effect) are needed

- Observational evidence suggest that high-mass stars may form via an accretion based formation scenario.

    - For B- to late O-type (proto)stars (up to 25-30 $M_{\odot}$): circumstellar disks with masses ≲ mass of the central star and radii of < 1000 au; centrifugally supported disks in (quasi-)Keplerian rotation and gravitationally stable

    - For early O-type (proto)stars (> 30 $M_{\odot}$): non-equilibrium, not centrifugally supported toroids with masses >> mass of central star(s) and radii of 10000 au. Accretion disks could be embedded inside rotating toroid