Initial conditions for massive star formation

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Zoom into \( \sim 29 \)

colorscale: GRS \(^{13}\)CO(1–0); contours: 850\(\mu\)m

- Becker HII
- MSX PS
- Szymczak CH\(_3\)OH

GLIMPSE 8\(\mu\)m + PdBI NH\(_2\)D
Remarks & Scope

• Literature growing rapidly!
  - Let me know of important work you might know of but which I did not cover

• Focus on observational side of initial stages

• Focus on “cold” stages before
  - IR bright MYSOs
  - Hot molecular cores
  - UCHII regions
Outline

• Introduction
  – Zoom into G29
  – Remarks & Scope
• Large scale environs:
  – Giant molecular clouds
  – Infrared Dark Clouds
• Searching for initial stages of MSF:
  – IR/maser selected
  – Dust surveys
• Cold clumps:
  – phys/chem. Properties
  – Dynamics
  – SEDs
  – Clump mass function
  – (Trigger?)
• Cores in IR-quiet clumps
• Summary & outlook
Cloud structure and Terminology e.g. Williams+ 2000

• GMC properties (from large scale CO surveys):
  - Diameters ~ 10 - 100 pc
  - Masses ~ $10^{5-6.5} M_\odot$
  - Mean densities ~ several 100 cm$^{-3}$ but strongly clumped

• Clumps:
  - Coherent, overdense structures in l-b-v
  - Might form/are forming whole clusters
  - *typical single dish mm telescope mapping targets*

• Cores:
  - Might form/are forming individual stars/multiple systems
  - *Usually interferometers needed to resolve them*
Two different interpretations of GMC observations

- **GMC as dynamic, transient objects (e.g. Ballesteros-Paredes+ PP V)**
  - Formed by large scale colliding gas flows
  - Lifetime ~ dynamical crossing time
- **Quasi-equilibrium self-gravitating objects (McKee 1999)**
  - Formed by large scale self-gravitating instabilities
  - Lifetime ~ many crossing times
- See e.g. McKee & Ostriker (2007) for more details

- **How can we identify cold parts of GMCs?**
Discovery of Infrared Dark Clouds

- ISOCAM: Perault+ 96
- MSX: Egan+ 98
- Detected by their absorption of the bright, diffuse MIR emission of the Galactic plane
Comparison: OMC vs G11.11

- can resemble high CD parts of GMCs
- But also many smaller clouds, down to “IR dark clumps”
- Depend on evolutionary state and geometry of GMC

Figure 1.1: *Left panel*: 1.2 mm dust continuum map of the Orion Molecular Cloud 1 (courtesy T. Stanke). *Right panel*: 850 μm map of G11.11-0.12 (Johnstone et al. 2003).
Ammonia in IRDCs

Pillai+ 2006
Searching for initial stages of MSF
Surveys to study early phases of MSF

- **IRAS colour selection criteria for UC HII regions (Wood & Churchwell 1989) -> UCHII regions \( \sim 10^5 \) yrs**
  - But are all these IRAS UC HIIIs really UC HIIIs?
  - --> Subsequently many hot cores found associated with the UCHIIIs

- **H$_2$O/CH$_3$OH masers might trace YSOs <10$^5$ yrs**
  - But maser amplification line-of-sight dependent!

- **New IR criteria for (radio-quiet) massive protostars**
  - Same UC HII criteria but no association w/ 5GHz continuum
  - Must be pre-UC HII – but are they all OB protostars?
  - Palla+, Molinari+ 1996-2002; Sridharan/Beuther+ 2002
  - Red MSX: Hoare+

- **But all of these searches probe already some form of ongoing SF and cannot (directly) identify an earlier cold precluster phase.**
Current studies for earlier cold phase

• Larger environs of targeted surveys:
  – Ultracompact HII regions: Hill+, Thompson+
  – IRAS color selected: Klein+, Sridharan+, Beltran+, Faundez/Garay+
  – CH$_3$OH maser selected: Hill+

• IRDC selected surveys:
  – Carey+, Teyssier+, Rathborne+

• Unbiased surveys:
  – Cygnus X, Motte+
  – NGC6334, Munoz+
  – ISOPHOT serendipity, Krause+
  – Galactic plane surveys
Images of CH$_3$OH and/or UCHII regions: Hill+ 2005/6

- SEST/SIMBA
- 131 SFR, 404 clumps, 253 mm only of which 45% w/o MSX MIR
- $\sim 100M_\odot$ sensitivity limit
- + SCUBA: $\beta$ dust
Southern extension of Palla/Molinari sample:
Beltran+ 2006

- 245 SFR
- 95 mm clumps w/o MSX
- Hill, Beltran mm-only less massive but assuming same T. could be same mass but colder
- Clump mass spectra
Outer Galaxy dust emission survey:

Klein+ 2005

- Continuum imaging of 47 IRAS selected SFR
- 128 mm clumps, 12 IR/Radio-quiet > 100M

![Histogram of cloud components and their MSX associations vs. mass bins.]

**Tentative Stages of Massive Star Formation**

<table>
<thead>
<tr>
<th>Stage</th>
<th>Morphology</th>
<th>Detectable at</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>0: PPcICs</td>
<td>Massive cloud core without collapse</td>
<td>mm</td>
<td>IRAS 06073+1249 core 2</td>
</tr>
<tr>
<td>1: Early protocluster</td>
<td>Massive stars have begun to form deeply embedded in the cluster</td>
<td>mm</td>
<td>IRAS 03211+5446 core 1</td>
</tr>
<tr>
<td>2: Protocluster</td>
<td>The forming massive stars begin to clear a cavity, an H II region begins to evolve</td>
<td>mm, FIR, radio</td>
<td>IRAS 05197+3355 core 1</td>
</tr>
<tr>
<td>3: Evolved protocluster</td>
<td>The cluster starts to emerge but is still embedded</td>
<td>mm, FIR, MIR, radio</td>
<td>IRAS 04329+5047 core 1</td>
</tr>
<tr>
<td>4: Young cluster</td>
<td>The cluster has emerged from its parental cloud</td>
<td>mm, FIR, MIR, NIR</td>
<td>IRAS 03211+5446 core 2</td>
</tr>
<tr>
<td>5: Cluster</td>
<td>The cluster has dispersed its parental cloud</td>
<td>MIR, NIR</td>
<td>IRAS 05345+3157, IRAS 05281+3412</td>
</tr>
</tbody>
</table>

Note.—The examples for stage 0 and stage 1 are of course pre-protocluster candidates, but the assignment to stage 0 and stage 1 is arbitrary.
SCAMPS: The SCUBA massive precluster survey:
Thompson+ 2005

- 13'x13' imaging of 37 UCHII clumps
  - 700 clumps
- See poster by Pestalozzi+
  - Masses sufficient for cluster formation, but luminosities still below O,B stars
  - -> early stage of cluster formation
Cold dust emission from IRDCs

Fig. 3.—Left: MSX 8 μm image showing the mid-infrared extinction of G28.34+0.06. Right: SCUBA scan map of 850 μm emission from the same region. The color scale of the SCUBA image has been adjusted to emphasize the structure of the clouds. Contours are overlaid on the burned-out core of P2 at the 3.0 and 4.5 Jy beam$^{-1}$ levels to show the location of this very bright pointlike source more clearly. The coordinate system, projection, and pixel spacing are the same as in Fig. 1. The intensity levels in the 8 μm image range from 10 to 60 MJy sr$^{-1}$. The 850 μm intensity range is from $-0.4$ to 1.6 Jy beam$^{-1}$. 
Massive high extinction clouds

- NICE method with GLIMPSE 3.5/4.5μm
- Select highest extinction peaks:
  - Many well known MSFR
  - Studied massive IRDCs
  - + new regions!
- MAMBO imaging, Ammonia, mm/submm follow ups
- --> Poster by Rygl+

- wide range of morphologies:
  - Diffuse
  - Core-halo
  - Multi-peaked, filamentary
• ISOPHOT serendipity
  – \( F(170) > 2 \, F(100) \)
  – \( \Rightarrow T_{\text{dust}} < 18 \)K

• Cold center: candidate for massive prestellar clump

Fig. 2. a) 850 \( \mu \)m continuum map of the compact ISOPHOT Serendipity Survey source FIR1, overlaid on a near-infrared \( JHK_s \)-composite constructed from 2MASS data. Three compact dust condensations (SMM 1, SMM 2 and SMM 3) are detected, which are located in a diffuse extended emission. Mid-infrared sources detected by the MSX-satellite are marked with boxes. The submillimeter knot SMM 2 is associated with a small cluster of embedded NIR sources (IRS 2–5) as detected by the 2MASS and MSX surveys. IRS 1 was identified as a very young Herbig B2 star by our follow-up spectroscopy. The two compact submillimeter sources SMM1 & SMM3 without any infrared counterparts are candidate Class 0 objects. The position of the very cold cloud core is indicated by an ellipse. Contour levels are starting at 67 and increasing by 33 mJy/beam. The size of the SCUBA beam is indicated in the lower right, the dashed circle corresponds to the ISOPHOT beam. b) The dust color temperature distribution across FIR 1 shows the presence of a very cold \( (T_d \sim 11 \) K) core at the center of the cloud. The temperature profiles towards north-east and south-west indicate an external heating by the infrared sources IRS 1–5. The temperature is calculated from the submillimeter spectral index between 450 \( \mu \)m and 850 \( \mu \)m, assuming a dust emissivity \( \beta = 2 \).
Large scale studies:
Cygnus X and NGC 6334
Motte+ 2007, Munoz+ 2007

Fig. 1.— Grey scale image of the 1.2 mm emission towards NGC 6334 and NGC 6357. The polygonal line was used to exclude the noisy borders of the mapped region. The large square indicates the area defined as NGC 6334 in the present analysis. It encloses 182 of the 347 clumps found using offgrid. Also labeled are the three sub-regions chosen for statistical analysis: the central region NGC 6334a (see Figure 2); a larger extension NGC 6334b; and finally NGC 6334c which includes only the clumps outside of NGC 6334b.

Fig. 2. Millimeter continuum imaging of the Cygnus X molecular cloud complex obtained with the MAMBO and MAMBO 2 cameras installed at the IRAM 30 m telescope. These 1.2 mm maps have been smoothed to an effective angular resolution of 15”, allowing a sensitivity of 0.1–5 pc cloud structures. The main radio sources (Dame & Rhoos 1986) and a few well-known sources are indicated as reference marks. The “CygX-North” region (see Fig. 1 for its location) maximum flux is ~ 8.5 mJy/beam; the color scale is saturated beyond 500 mJy/beam and rms noise level is ~ 10–20 mJy/beam.1
Galactic Plane surveys

- **ATLASGAL**
  - LABOCA @ APEX
  - --> GC
- **BOLOCAM**
- **SCUBA2**
- **MIPSGAL !!**
- **Herschel**
- --> Krause talk
Summary:
Searching for initial stages

- Current surveys produce large numbers of cold massive clumps!
- Statistics for very massive clumps which might turn into rich OB clusters still small --> Galactic plane surveys needed
- Variety of selection criteria yield sources in a variety of environs:
  - with/without powerful OB clusters nearby
  - Range of locations throughout the Galaxy
- Some follow ups to determine their properties completed (--> next section of talk), several still ongoing
Massive cold clump properties

- Physical conditions: R, M, n, T
- Spectral Energy Distributions
- Infall
- Chemistry
- Clump mass functions

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- NGC2264, CygX, some IRDC results --> Talks Motte, Peretto, Jackson
Cold clumps from Faundez sample

- Garay+ 2004
- Note: R, M, n similar to cores with IRAS and/or UCHII sources, but Tdust much lower
- Later studies:
  - Rathborne+ 2006: evidence for massive YSOs in G34
  - Beuther+ 2006: MSF in G18

**TABLE 2**

<table>
<thead>
<tr>
<th>SIMBA SOURCE (1)</th>
<th>$D$ (kpc) (2)</th>
<th>$R$ (pc) (3)</th>
<th>$T_d$ (K) (4)</th>
<th>$M$ (5) ($M_\odot$)</th>
<th>$n$ (6) (cm$^{-3}$)</th>
<th>$R$ (7) (pc)</th>
<th>$M_{\text{vir}}$ (8) ($M_\odot$)</th>
<th>$n$ (9) (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G305.136+0.068</td>
<td>3.4</td>
<td>0.27</td>
<td>$&lt;16$</td>
<td>$1.1 \times 10^3$</td>
<td>$2 \times 10^5$</td>
<td>0.30</td>
<td>$1.1 \times 10^3$</td>
<td>$2 \times 10^5$</td>
</tr>
<tr>
<td>G333.125−0.562</td>
<td>3.5</td>
<td>0.34</td>
<td>$&lt;17$</td>
<td>$2.3 \times 10^3$</td>
<td>$2 \times 10^5$</td>
<td>0.68</td>
<td>$2.2 \times 10^3$</td>
<td>$3 \times 10^4$</td>
</tr>
<tr>
<td>G18.606−0.076</td>
<td>3.7</td>
<td>0.20</td>
<td>$&lt;15$</td>
<td>$4.0 \times 10^2$</td>
<td>$2 \times 10^5$</td>
<td>3.7</td>
<td>$2.5 \times 10^2$</td>
<td>$3 \times 10^4$</td>
</tr>
<tr>
<td>G34.458+0.121</td>
<td>3.8</td>
<td>0.24</td>
<td>$&lt;17$</td>
<td>$7.8 \times 10^2$</td>
<td>$2 \times 10^5$</td>
<td>0.64</td>
<td>$1.5 \times 10^3$</td>
<td>$2 \times 10^4$</td>
</tr>
</tbody>
</table>

$^a$ Lower limit.
• Massive H$_2$O and SIMBA clumps vs. Myers LMSF sources

• Scaling relations similar to LM sources but dv, n considerably higher
Ammonia properties of massive clumps in IRDCs

Pillai+ 2006

- Comparison of
  - IRDC clumps (black)
  - HMPOs (red)
  - Hot cores (stars)

- IRDC $dv$ smaller but still higher than LMSCs
- Clear temperature trend
Detailed modeling of IRDCs clumps: Ormel+ 2005

- Dust continuum + HCO$^+$
- Heating, increase of turbulence in all 3 cores

<table>
<thead>
<tr>
<th>Core</th>
<th>$p$</th>
<th>$M$ $[M_\odot]$</th>
<th>$R$ $[']$</th>
<th>$L$ $[L_\odot]$</th>
<th>$\chi^2$</th>
<th>$\langle \tau_{8.3 \mu m} \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>$2.2^{+0.3}_{-0.2}$</td>
<td>$91^{+22}_{-21}$</td>
<td>$37^{+5}_{-7}$</td>
<td>$330^{+270}_{-180}$</td>
<td>12.6</td>
<td>0.53</td>
</tr>
<tr>
<td>P2</td>
<td>$2.0^{+0.3}_{-0.5}$</td>
<td>$100^{+30}_{-28}$</td>
<td>$41^{+9}_{-7}$</td>
<td>$300^{+1000}_{-230}$</td>
<td>7.5</td>
<td>0.55</td>
</tr>
<tr>
<td>EP</td>
<td>$2.2^{+0.3}_{-0.2}$</td>
<td>$130^{+25}_{-24}$</td>
<td>$51^{+7}_{-7}$</td>
<td>$19^{+110}_{-17}$</td>
<td>2.2</td>
<td>0.58</td>
</tr>
</tbody>
</table>

$^a$ Angular radius. A linear radius of 0.1 pc corresponds to $R = 7.65''$.
ISOPHOT detections: Birkmann+ 2006

- ISOPHOT serendipity
- 16.5/12 K
- 75/280 M
- Infall spectra but also outflow wings

Fig. 5.—Spectra of the NH$_3$ ($J, K$) = (1, 1) and (2, 2) inversion transitions toward ISOSS J18339−0221 SMM2. A fit to the hyperfine structure of the (1, 1) line is also shown.

Fig. 6.—H$^{12}$CO$^+$ (3−2) and H$^{13}$CO$^+$ (3−2) taken at SMM1. The vertical dashed line marks the central velocity of the optical thin line; the optically thick transition shows redshifted self absorption.
Spectral energy distributions

- Rathborne+ 2006
- Birkmann+ 2006
- Beuther+ 2007

Fig. 2.—Spectral energy distribution of IRDC 18223-3. The dots with error bars mark the detections at 24 and 70 µm on the short-wavelength Wien side of the peak, and at 1.2 and 3.2 mm on the Rayleigh-Jeans part of the spectrum. The four stars below 10 µm show the Spitzer IRAC upper limits in the near-infrared. The solid line presents a two-component fit with one cold component at \(~15\) K and one warmer component at \(~51\) K. The two dotted lines show the two components separately. The resulting physical parameters for each component are labeled accordingly.

Fig. 3.—Broadband continuum SED for the three cores. Included on this plot are peak fluxes at 24 µm, 350 µm, 450 µm, 850 µm, and 1.2 mm. The curves are graybody fits to the data, which yield values of \(\beta \sim 1.8\), \(T_{\text{.cluster}} \sim 0.25\), and \(T_{\text{peak}} \sim 33\) K (15' source diameter; see also Table 2). The derived bolometric luminosities are labeled for each core. MM1 saturates the MIPS array; hence, the quoted 24 µm flux is a lower limit.

Fig. 4.—Spectral energy distribution of ISOSS J18364-0221. For wavelengths longer than 100 µm, the SED is dominated by the optically thin thermal emission of large grains and well fitted with a modified blackbody with an emissivity index of \(\beta = 2\); the point at 60 µm is not taken into account.
Evidence for infall

- **HMPOs**, Fuller+ 2005: $0.2-1 \times 10^{-3} \, M_\odot /\text{yr}$
- **UCHIIs**, Keto++, Wyrowski+ 2006
- H2O maser dense clumps, Wu+ 2003: B/R statistics similar to low mass clumps
- Possible earlier stages:
  - G25.38, Wu+ 2005: $3.4 \times 10^{-3} \, M_\odot /\text{yr}$
  - ISOSS J18339, Birkmann+ 2006
  - Check also SCAMPS and high extinction clouds posters (Pestalozzi+, Rygl+)
MM lines from IR dark clumps: Beuther&Sridharan 2007

- Mm lines towards 43 IR dark clumps
- SiO: 18 sources --> SF
- $\Delta v(\text{H}13\text{CO}^+)>\Delta v(\text{NH}_3\ 11)$: increase of turbulence to denser inner part
- CH$_3$CN 14%, CH$_3$OH 40%
  - CH$_3$OH abundance close to values of low mass cores
Deuterium fractionation: Fontani+ 2006

- IRAS selected HMPOs
  - CO depletion
  - N2H+ deuteration
- Cold dense gas remnant from the HMPO formation or secondary cores in the beam?

![Graph](image)

**Fig. 2.** Deuterium fractionation ($D_{\text{frac}}$) versus integrated CO depletion factor ($f_D$) for our sources (filled circles) and the low-mass pre-stellar cores of Crapsi et al. (2005) (open squares). The arrows indicate the upper limits on $D_{\text{frac}}$ (see Table 9) or the lower limit on $f_D$ (see Table 11).
Deuterium fractionation:

Pillai+ 2007

- SCAMPS and clumps in IRDCs
  - CO depletion
  - NH2D deuteration
- \([\text{NH}_2\text{D}]/[\text{NH}_3]\) \(\sim 0.005-0.6\)
  - Low values are lower limits
  - \(\rightarrow\) largest deuteration so far measured in massive clumps

- No trend with T, except deuteration low above 20 K
- Roueff+ 2005: steady state gas phase chem.
- Roberts+ 2003, \(n \sim 3\times10^6\):
  \([\text{NH}_2\text{D}]/[\text{NH}_3]\) \(\sim 0.4-0.8\)
Clump mass functions: Reid & Wilson 2006ab

- .5.5x5.5 pc SCUBA image of M17
- > 100 clumps
- Clump mass function either
  - Double power law
  - Lognormal
- 22 low+high mass regions:
  - LM: best fit w lognormal
  - HM: double power low
  - alpha_high close to Salpeter value
Clump mass functions: Beltran+ 2006, Munoz+ 2007

- High mass clumps consistent with Salpeter like slopes
Summary: Properties of massive cold clumps

- High masses and densities in comparison to their low mass cousins
- Clump mass functions: Salpeter like for high mass end, still some scatter, T dependence might be needed for M
- Infall: ongoing through a large variety of stages!
- Evidence for depletion and, for some sources, deuteration as high as low mass cousins
- Range of star formation activity still hiding in the clumps!
  - --> Check SF activity with high angular resolution studies
Cores (interferometric studies)
G28.34+0.06: Small Scale Structure

Wang+ 2007

NH$_3$ in contour, 8micron in color

Northern Region
L $\sim 10^4$ L$_{\odot}$, H$_2$O maser
T $> 30$K.  v $> 3.5$ km/s
Protostellar Core

Southern Region
Quiescent cores
T $< 20$K  v $< 2$ km/s

Wang et al. 2007
G28.34 quiescent region: temperature and clump mass spectrum

Wang+ 2007

Gas externally heated

Internal heating

Salpeter -1.4

Cumulative Mass Function

Clumps found in G28.34+0.06 southern region

A = -0.13(0.01)

A = -1.5(0.1)
**PdBI images of IRDCs:**

**Rathborne+ 2007**

- PdBI study of 4 clumps in IRDCs
- $\rightarrow$ 12 cores
- 1 hot core!
- Hierarchical fragmentation

![Image of PdBI images of IRDCs](image-url)

**Fig. 4.** — *Top left:* Spitzer/MIPS 24 $\mu$m image (6" angular resolution) of G024.60+00.08 overlaid with contours of 1.2 mm continuum emission obtained with the IRAM 30 m telescope (11" angular resolution; contour levels are 30, 60, 90, 120, 180, 240, 300 mJy beam$^{-1}$). The boxes outline the extent of the high-resolution images. *Top right:* IRAM Plateau de Bure Interferometer 1.3 mm (upper) and 3 mm (lower) continuum images toward core MM2 overlaid with the lower resolution 1.2 mm continuum emission (contour levels are 90, 120, 180, 240, 300 mJy beam$^{-1}$). *Bottom:* IRAM Plateau de Bure Interferometer 1.3 mm (left) and 3 mm (right) continuum contour images of core MM2 (1.3 mm contour levels are -4, 4, 4.5, 5, 6, 7, 8, 9 mJy beam$^{-1}$; 3 mm contour levels are -1.2, 1.2 [5σ] in 3.2 m steps of 0.3 mJy beam$^{-1}$ and 3.5 to 6 in steps of 0.5 mJy beam$^{-1}$). Marked on these images are the condensations identified within the core (the cross centers mark the center of the Gaussian fits; their sizes and position angles correspond to the beam). Table 3 lists their properties. Note that the bright core MM2 is resolved into five condensations (A, B, C, D, and E). The close proximity of these condensations suggests that this core is forming a protocluster.
IRDC 18223-3
Beuther + 2006

- 180 M⊙
- Outflow
- Turbulence increase to center
- Quiescent secondary core
\( \text{N}_2\text{H}^+ \) ATCA/APEX results

Wyrowski+ 2007

- Compact 3mm cont/CH3CN source offset from UCHII
- \( \text{N}_2\text{H}^+ \) 1-0 constrains \( N_{\text{col}} \) and \( T_{\text{kin}} \) (20K)
- Density: line ratios of higher transitions
  \( \Rightarrow n > 5 \times 10^6 \text{ cm}^{-3} \)
- Core sizes 0.1–0.2 pc
- \( M > M_{\text{vir}} \): unstable

\( \Rightarrow \) Promising candidates for massive pre/proto stellar cores
Interferometric observations of deuterated ammonia

Pillai 2006
SMA dust cont + $N_2H^+$ from pre-protostellar cores

Pillai+ poster

- 1mm continuum: 60 – 800 $M_\odot$
- Mean densities $\sim 2 \times 10^6$ cm$^{-3}$
- 12/15 cores w/o MIR
- Strong $N_2H^+$ (3-2), narrower lines (1 km/s) towards starless cores
- Velocity dispersion of cores in a clump $\sim 5$ km/s

Figure 1: MIPS 24 micron emission (colorscale) with 279 GHz continuum emission from SMA subcompact configuration observations overlaid
Conclusions & Outlook

- Prolific times for the identification of precluster clump candidates!
- Properties of clumps fairly well known now
- Many cases, where SF activity can be found on a closer look.
  - Good: these clumps turn into stars
  - Bad: pure “starless” objects still rare
- For better statistics unbiased large scale surveys are on the way in a variety of wavebands
  - Submm bolometer surveys
  - MIR/FIR (MIPSGAL + Herschel in the future)
- Core properties will be stronger constrained by high resolution studies (with ALMA on the horizon)

Yes, Malcolm, we are making progress!!