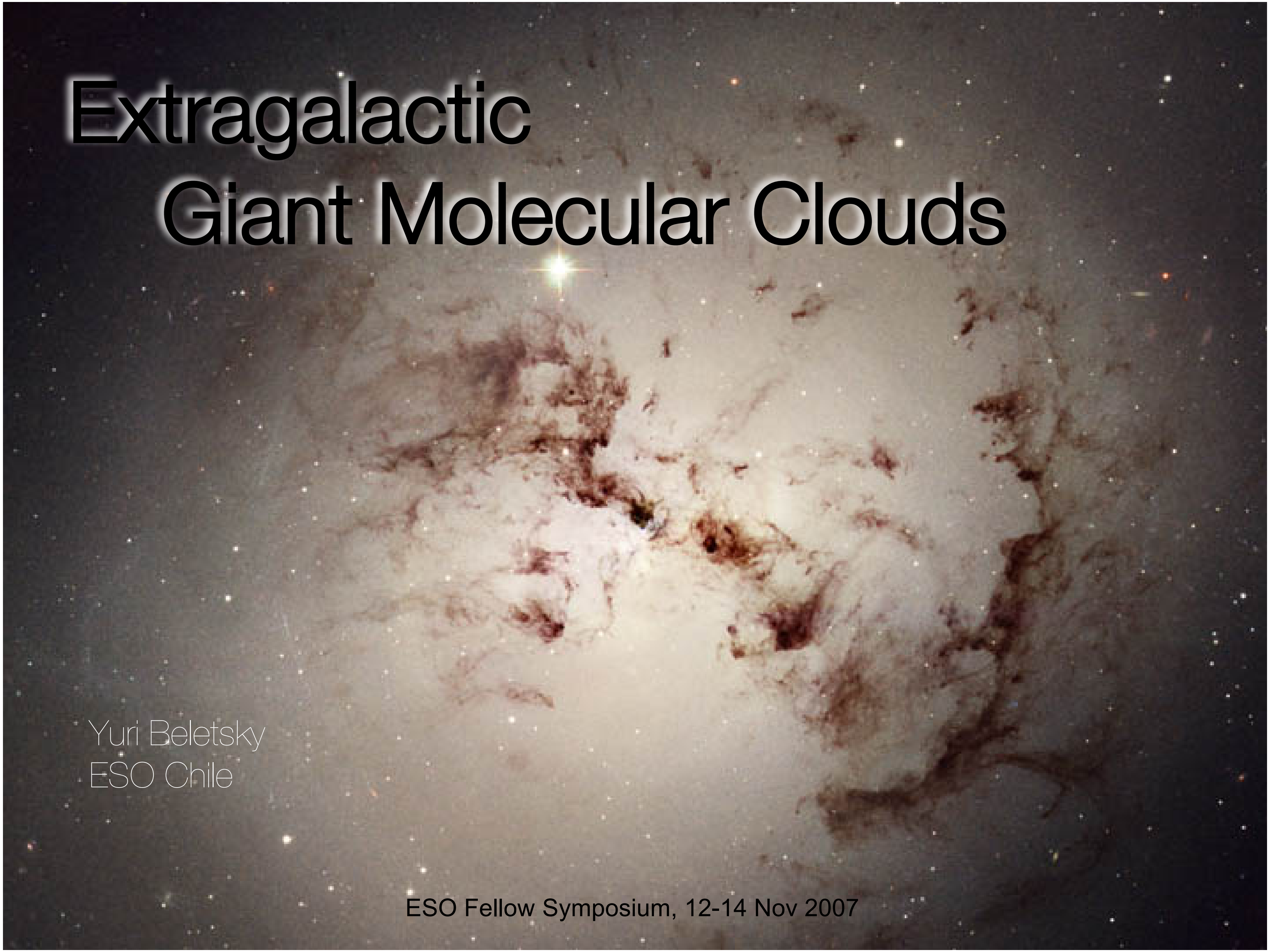
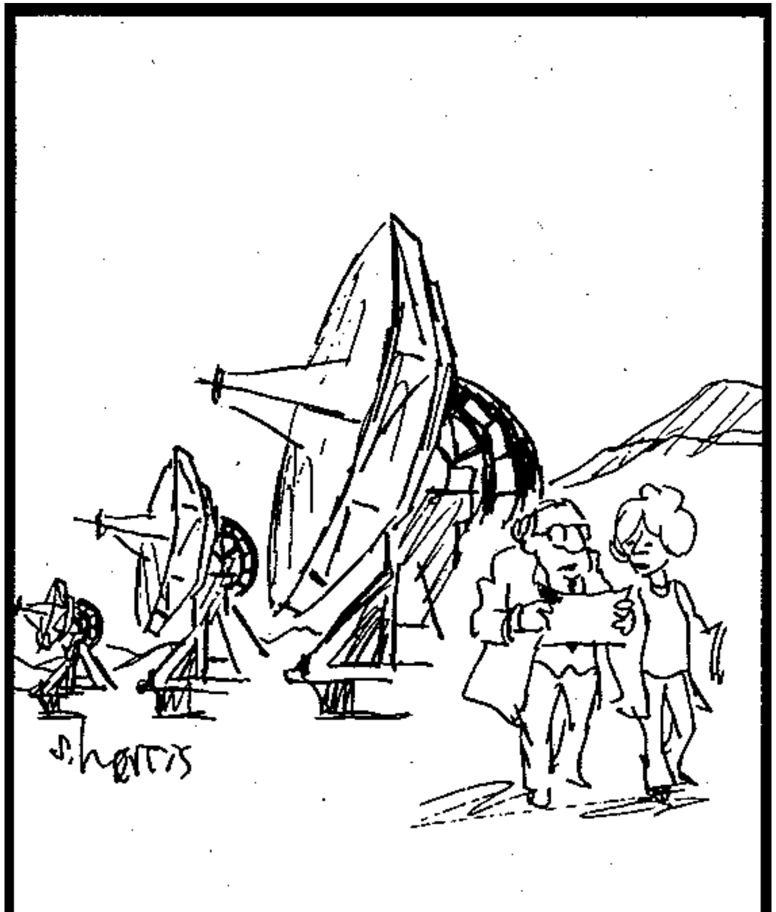


Extragalactic Giant Molecular Clouds

Yuri Beletsky
ESO Chile

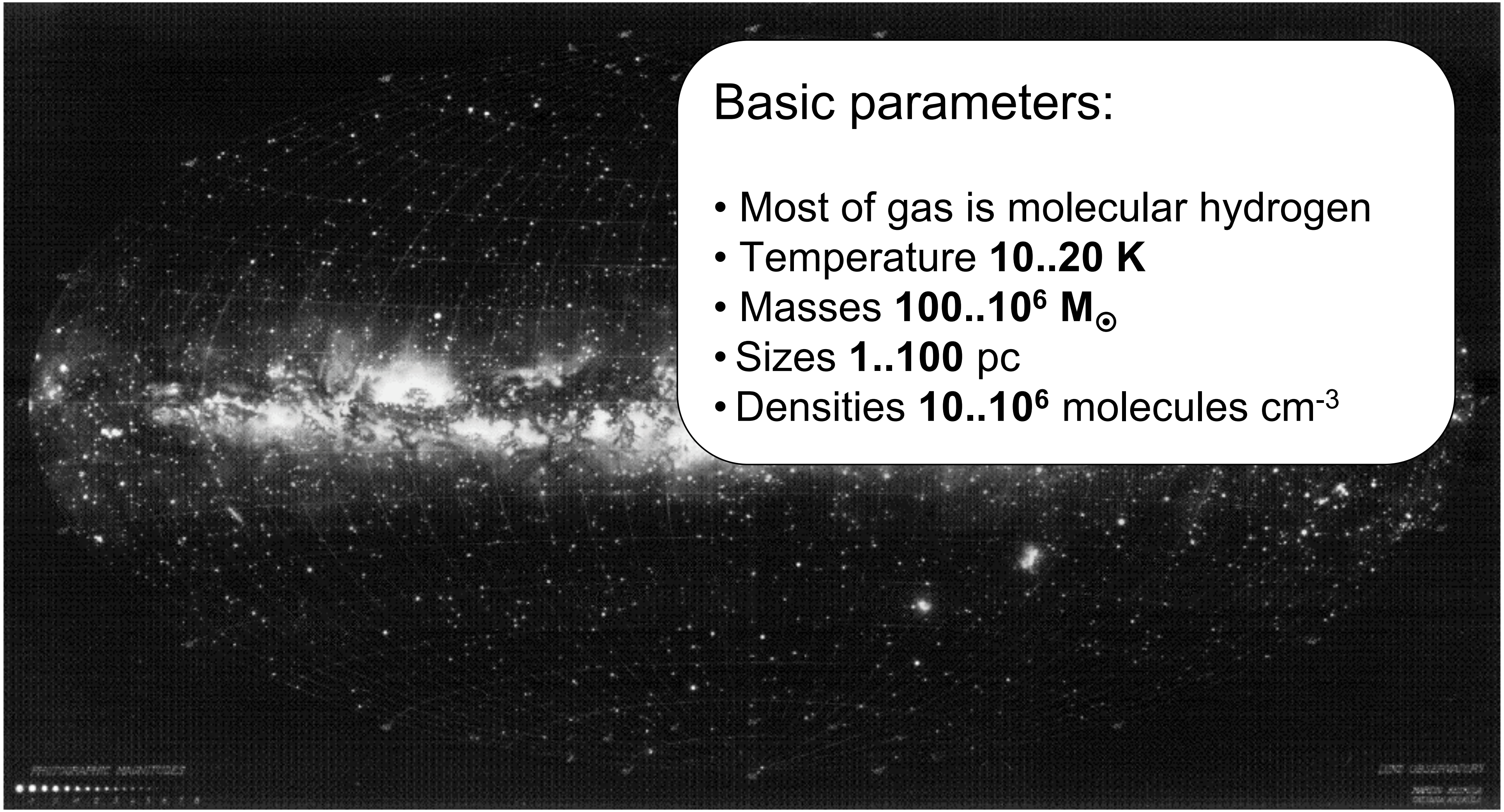
ESO Fellow Symposium, 12-14 Nov 2007

In the Beginning …



"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."

Molecular clouds

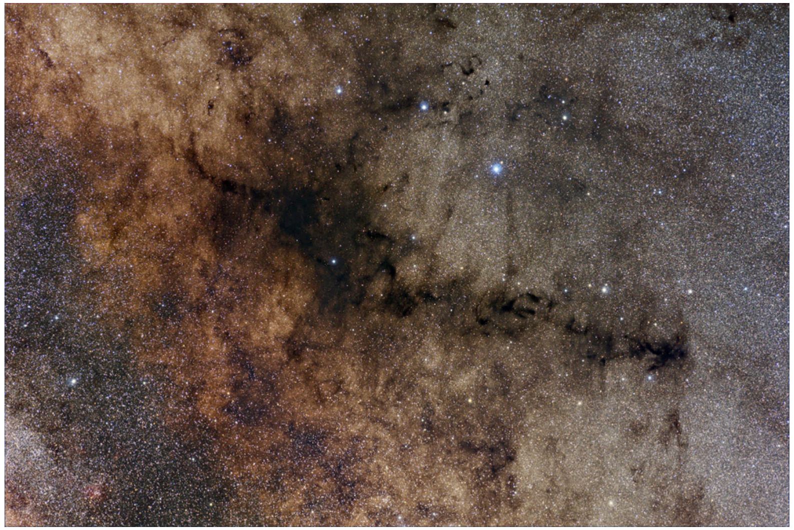


Basic parameters:

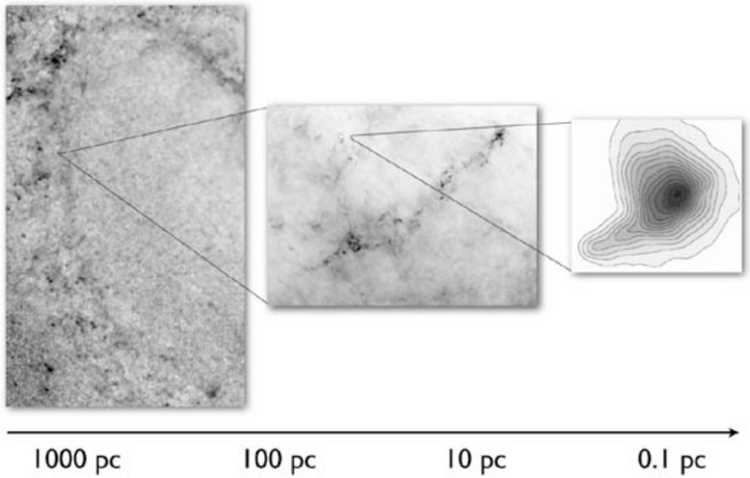
- Most of gas is molecular hydrogen
- Temperature **10..20 K**
- Masses **100..10^6 M$_\odot$**
- Sizes **1..100** pc
- Densities **10..10^6** molecules cm^{-3}

Molecular clouds structure

- Most molecular gas in the ISM is in Giant Molecular Clouds, with masses of 10^{5-6} M_{sun}, sizes of tens of pc, and average H_2 (prime constituent) densities of about 100 cm^{-3}



- Very inhomogeneous in density, with a lot of substructure (clumps and cores).



Why do we care about GMCs ?

- Most contemporary star formation occurs in giant molecular clouds (GMCs)
- Such clouds are also a principal component of the interstellar medium.

The questions:

1. What is the origin of the mass spectrum of the GMCs?
2. How is the supersonic turbulence in the GMCs generated and maintained?
3. Why is the efficiency of star formation in GMCs as low as a few percent?
4. What is the fate of the majority of the GMC material that is not turned into stars?
5. What is the lifetime of a GMC? Theoretical understanding of these issues must be guided closely by observations.

Observations of the Galactic GMCs are hampered by our location in the Galactic plane. As a result, the spatial distribution and, more importantly, the environments of the GMCs are uncertain.

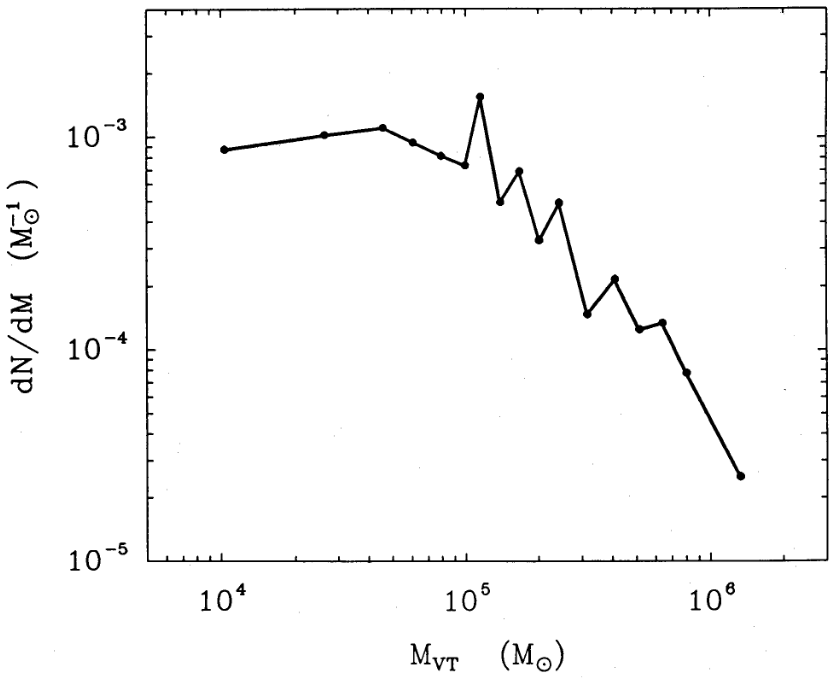
… OTHER GALAXIES ?

Mass spectrum from molecular observations:

$$dN/dM \propto M^{-1.53\pm0.07}$$

Solomon et al. 1987

1. Star formation efficiency is low because most molecular mass is in large, low-density, “inactive” structures.
2. On the other hand, this assures existence of relatively massive clumps where massive stars and clusters can form (if mass spectrum were steeper we would have mostly low mass stars).



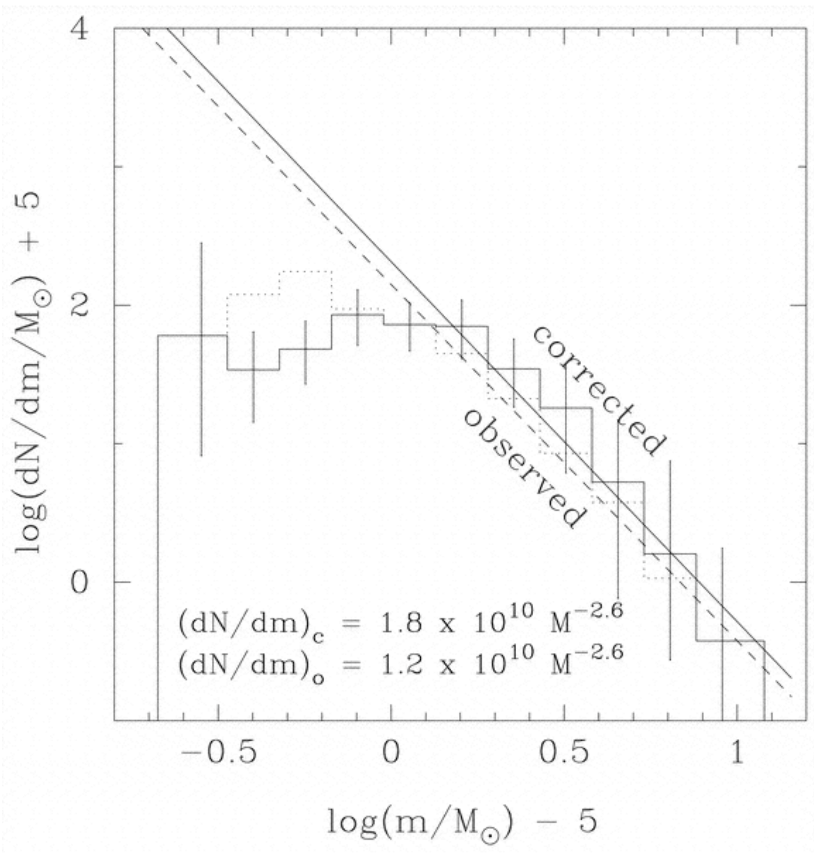
Both gravitational fragmentation (Fiege & Pudritz 2000) and turbulent compression and fragmentation (Vazquez-Semadeni et al. 1997) models can produce mass spectra similar to that observed.

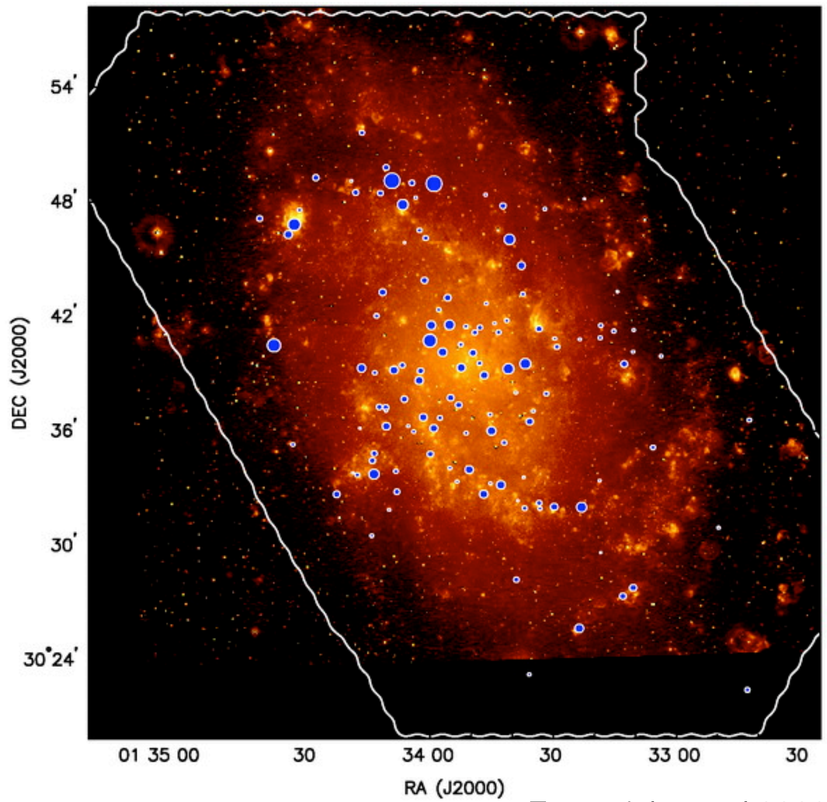
Connection to star formation:

• Quasistatic star formation: Interplay between gravity and magnetic support (modulated by ambipolar diffusion). Clouds should live for 10^7 years.

• "Turbulent" or "dynamic" star formation: Interplay between gravity and supersonic turbulent flows. Clouds should live for only a few times 10^6 years.

GMCs in M33 (CO-data)





Engargiola et. al 2003

Parameters of Mass Spectra for GMCs in Local Group Studies

Object	Name	Type	Number	γ	N_0	$M_0/(10^5\ M_\odot)$
Inner MW...	SRBY	VT	190	-1.53 ± 0.07	36. ± 12.	29. ± 5.0
		CO	173	-1.53 ± 0.06	27. ± 11.	41. ± 9.5
Inner MW...	SYSCW	VT	107	-1.58 ± 0.15	14. ± 10.	26. ± 7.6
		CO	97	-1.41 ± 0.12	21. ± 13.	29. ± 7.2
Outer MW[a]...	HCS	VT	227	-2.56 ± 0.11	...	3.2 ± 0.78
		CO	81	-2.06 ± 0.15	...	6.3 ± 3.1
Outer MW...	BKP	VT	336	-2.29 ± 0.08	4.5 ± 3.5	2.9 ± 1.0
		CO	81	-2.16 ± 0.17	2.7 ± 2.9	2.0 ± 1.0
M33...	EPRB	CO	58	-2.85 ± 0.36	2.5 ± 2.7	8.6 ± 3.3
LMC...	NANTEN	VT	44	-1.71 ± 0.19	10. ± 6.5	23. ± 4.6
		CO	55	-1.72 ± 0.12	6.1 ± 3.6	82. ± 32.

Rosolowsky 2005

Tracing the clouds …

CO – is a typical tracer of molecular hydrogen,

however:

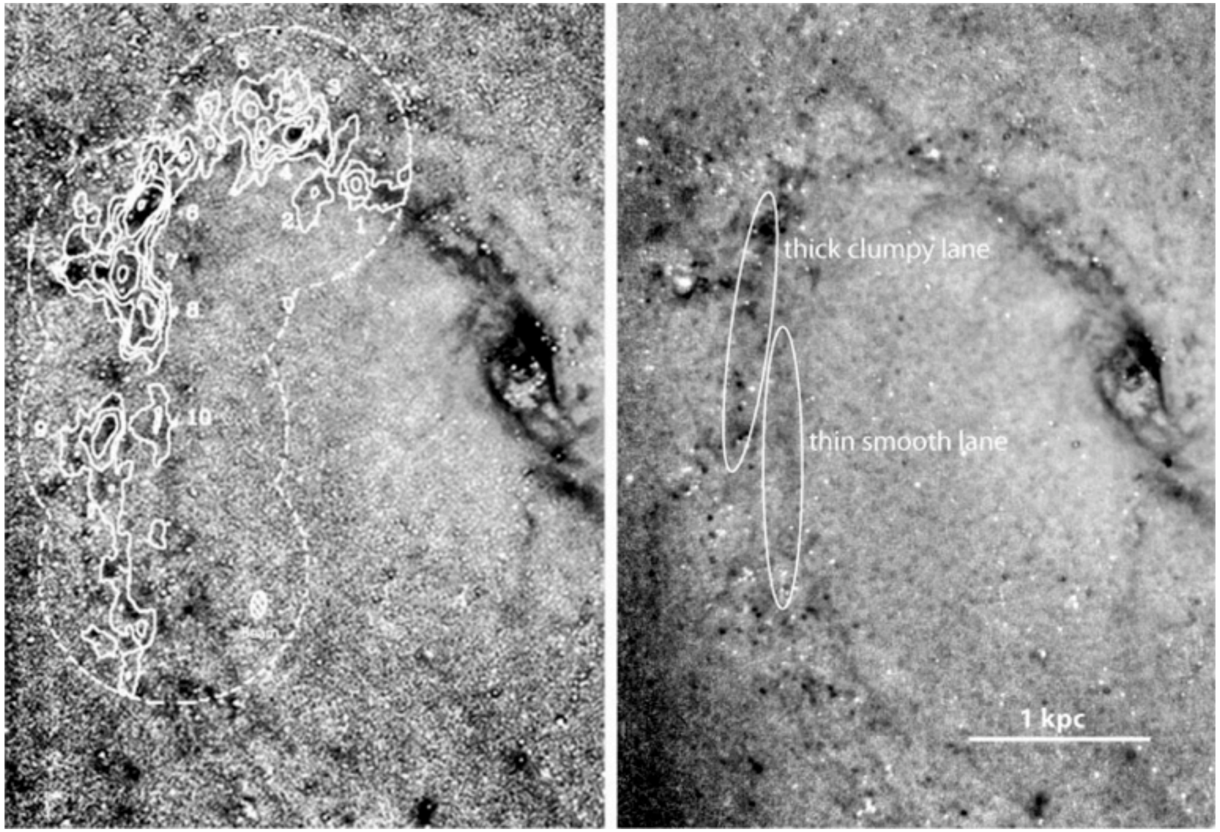
.. other galaxies galaxies are **far away** =>

- sensitivity is low
- resolution is poor (several clouds in the beam)
- complicated tracer (temperature, depletion, etc.)

Can we find another tracer ?

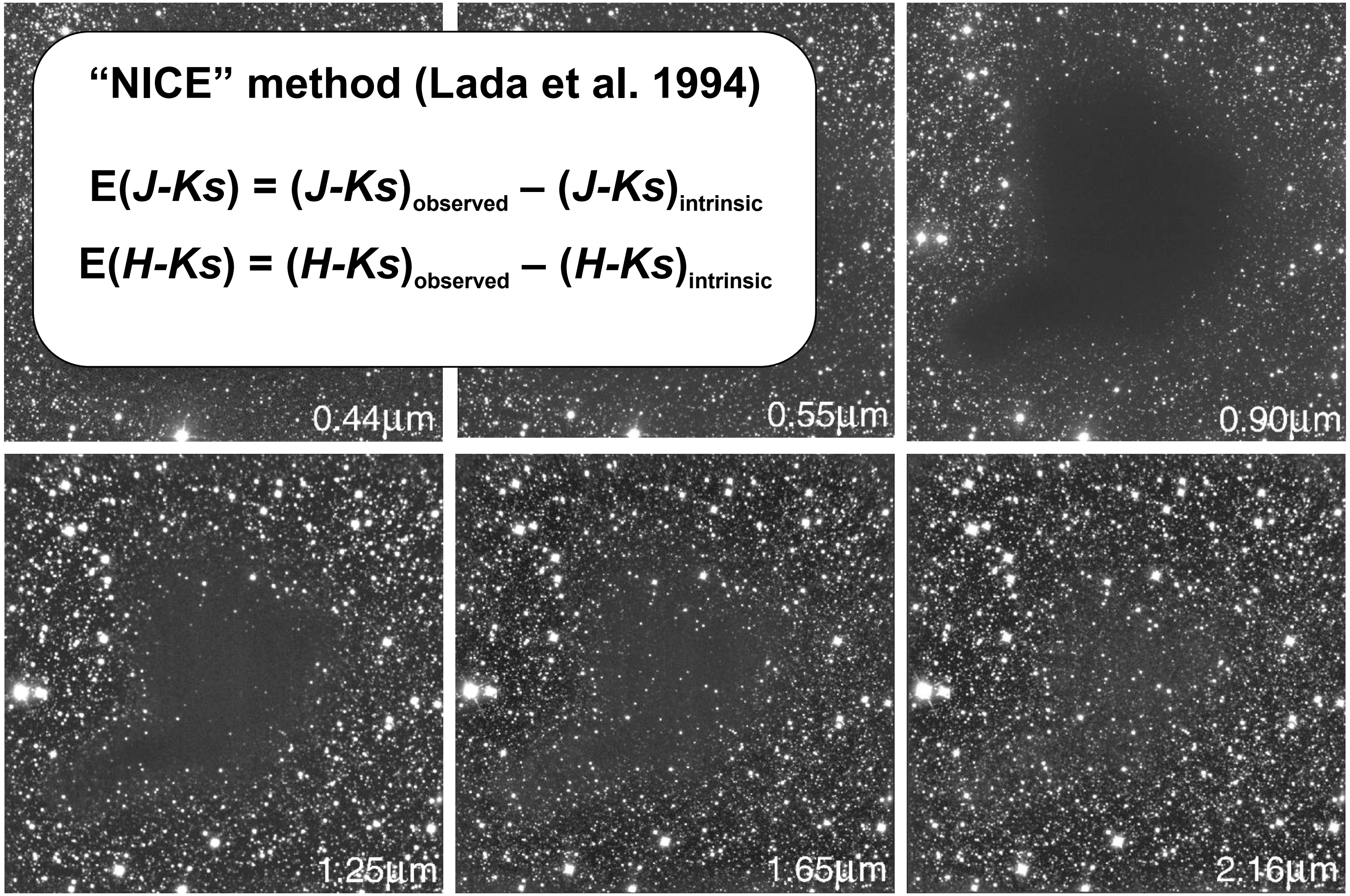
CO - dust correlation:

The good CO-dust correlation is a very strong indication that CO traces the H_2 column density.



(M83, J-K color map, NTT/SOFI)

Counting stars



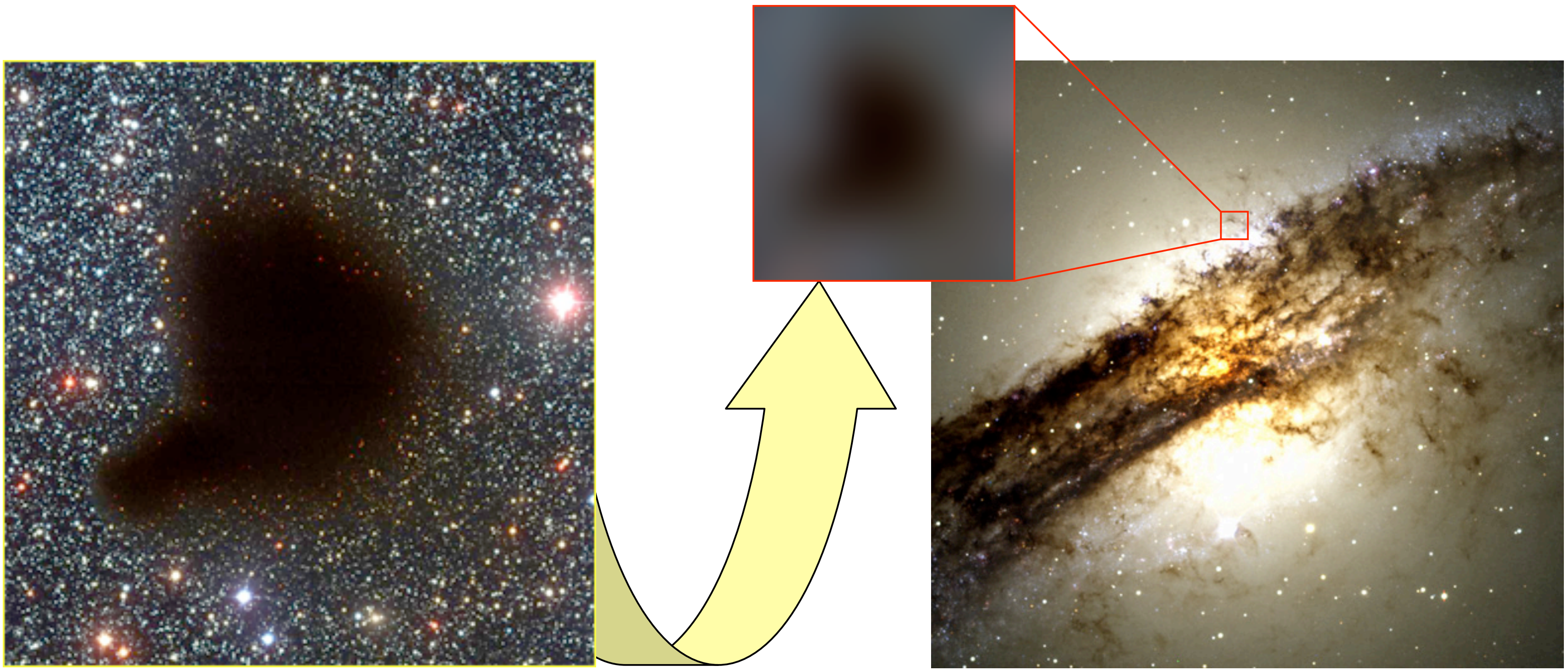
"NICE" method (Lada et al. 1994)

$$E(J\text{-}Ks) = (J\text{-}Ks)_{observed} - (J\text{-}Ks)_{intrinsic}$$

$$E(H\text{-}Ks) = (H\text{-}Ks)_{observed} - (H\text{-}Ks)_{intrinsic}$$

Going extragalactic

Instead of measuring the color of thousands of background stars to molecular clouds, we measure the ***average color*** of the unresolved thousands stars that will fall on a pixel of NIR detector.

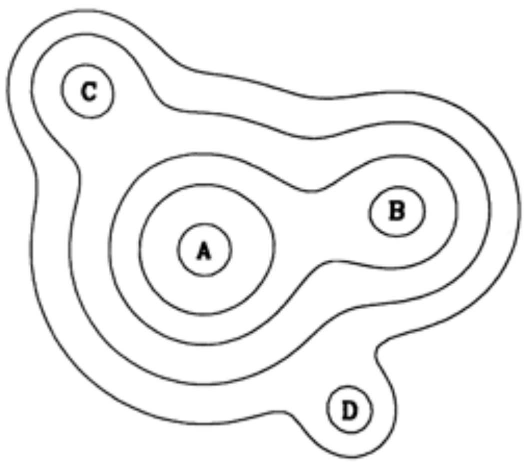


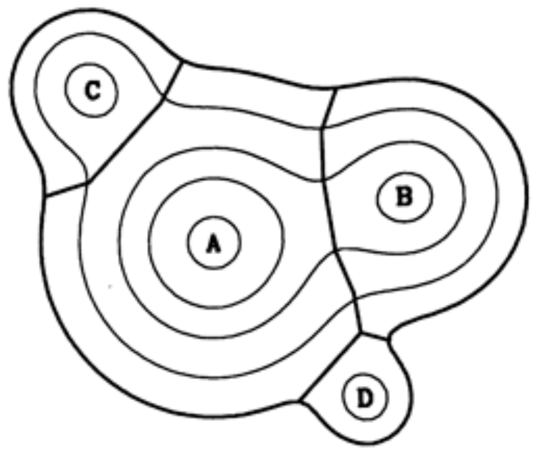
Sample selection

All the images (c) Robert Gendler

Locating the clouds - part 1

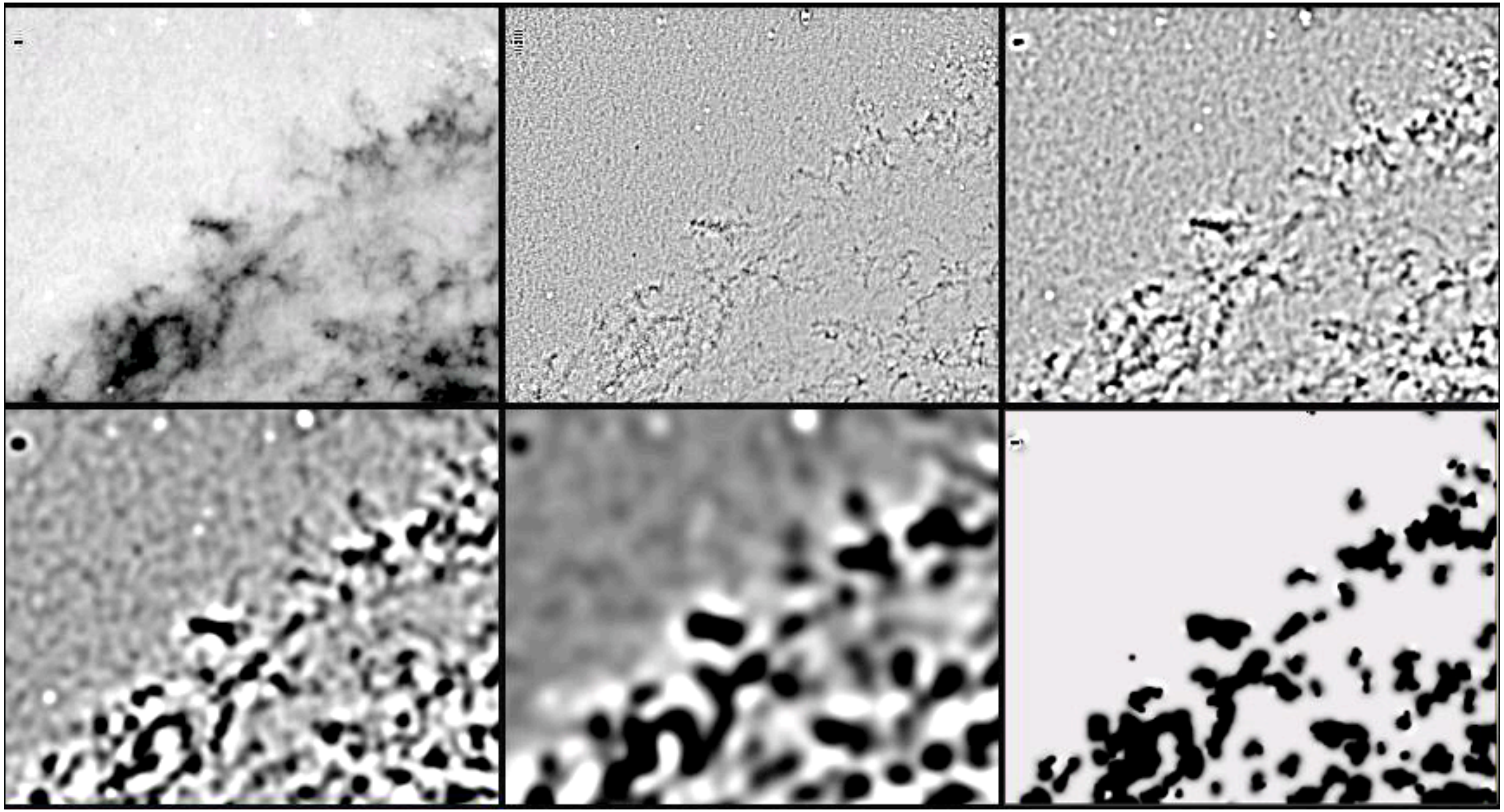
- "Clumpfind" algorithm, proposed by Williams et al. 1994
- the algorithm works by first contouring the data at multiple of the *rms* noise of the observations, then searches for local maxima which locates the clump, and then follows them down to lower intensities
- no *a priori* clump profile is assumed





Locating the clouds - part *Deux*

B-spline cubic wavelet transform



BSpline Cubic Wavelet Transform

- The image is projected in different Resolutions (version more and more smoothed of an image)
- Wavelets are the details lost from one resolution to the next one

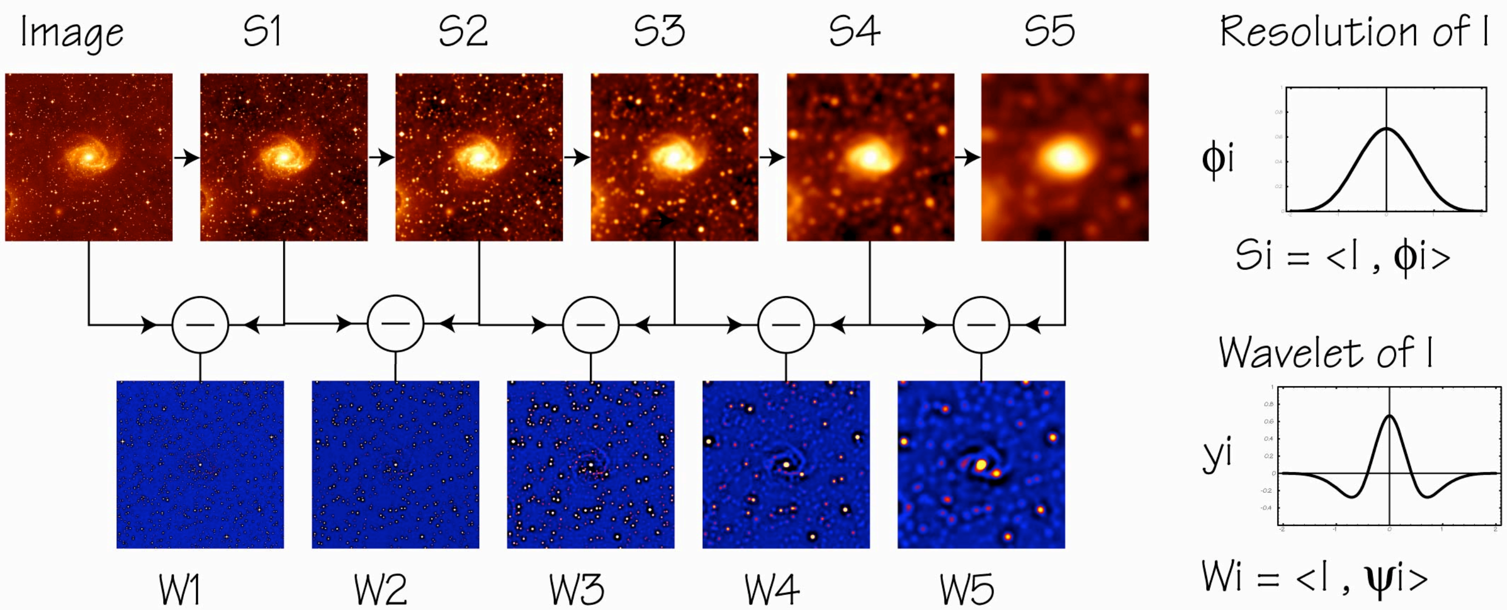
i Scale of the resolution

ϕi Smooth function at scale i

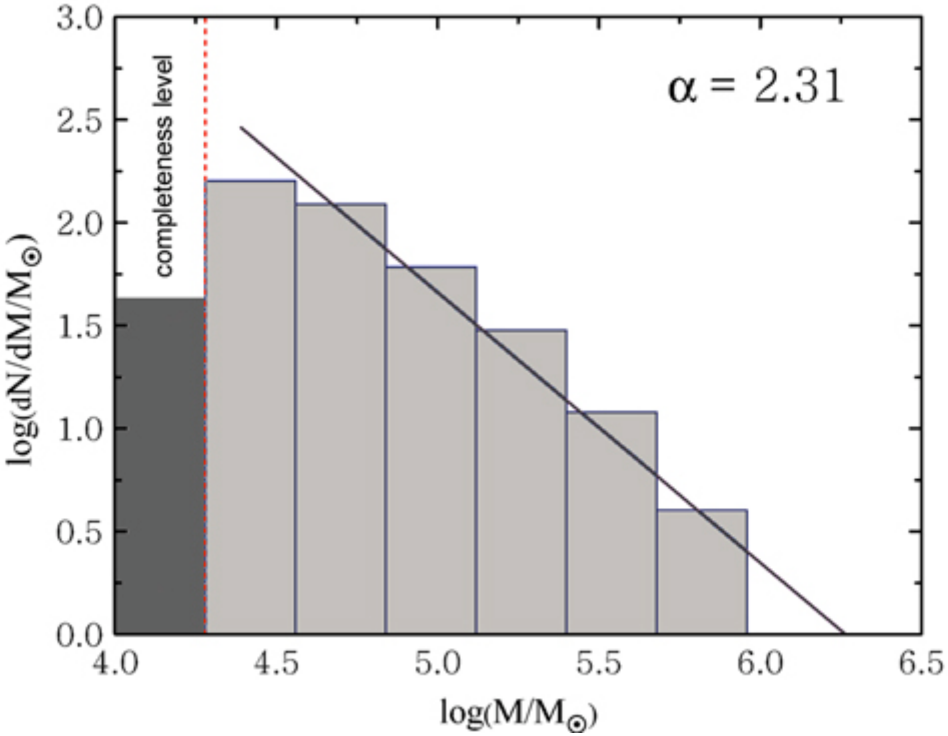
ψi Wavelet function at scale i

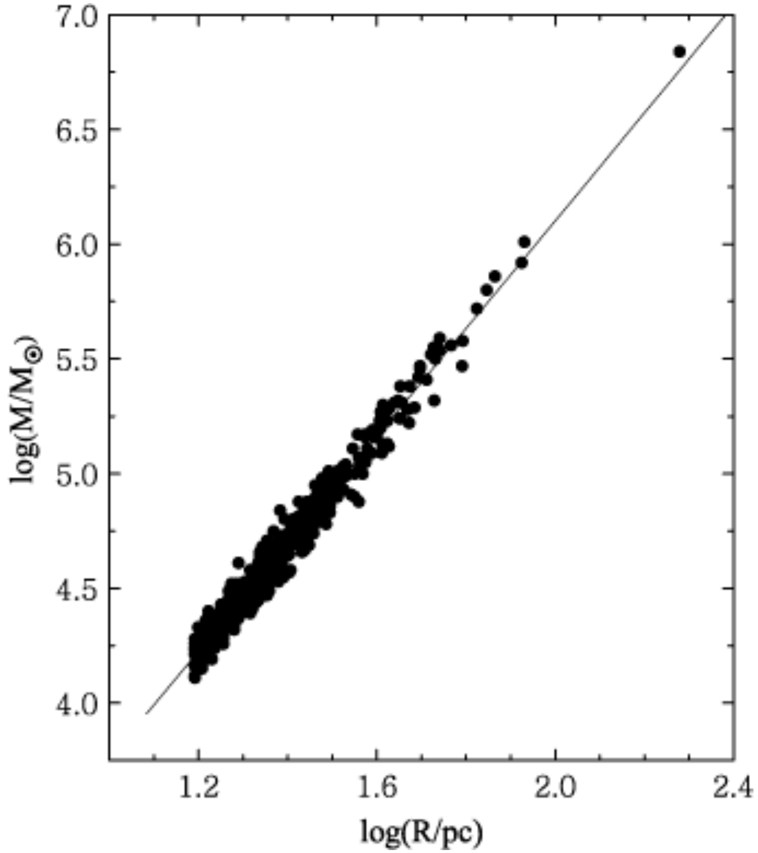
$\psi i = \phi(i-1) - \phi i$

ϕi and yi are dilated by 2 between each scale.



The mass spectrum (for NGC5128)

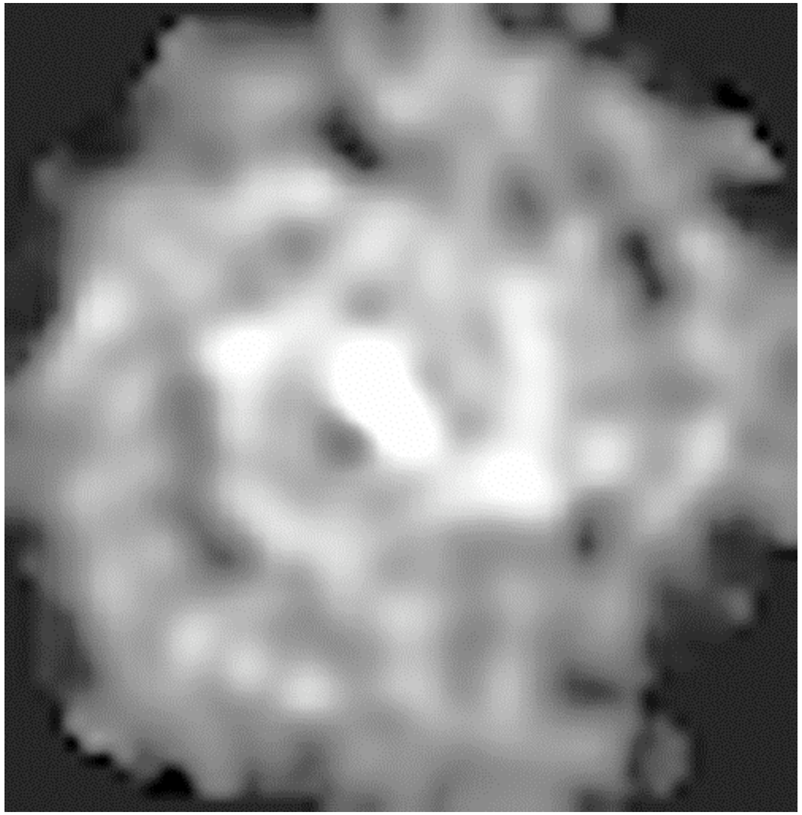




M83: extinction mapping *vs* CO

The total mass of molecular gas derived using:

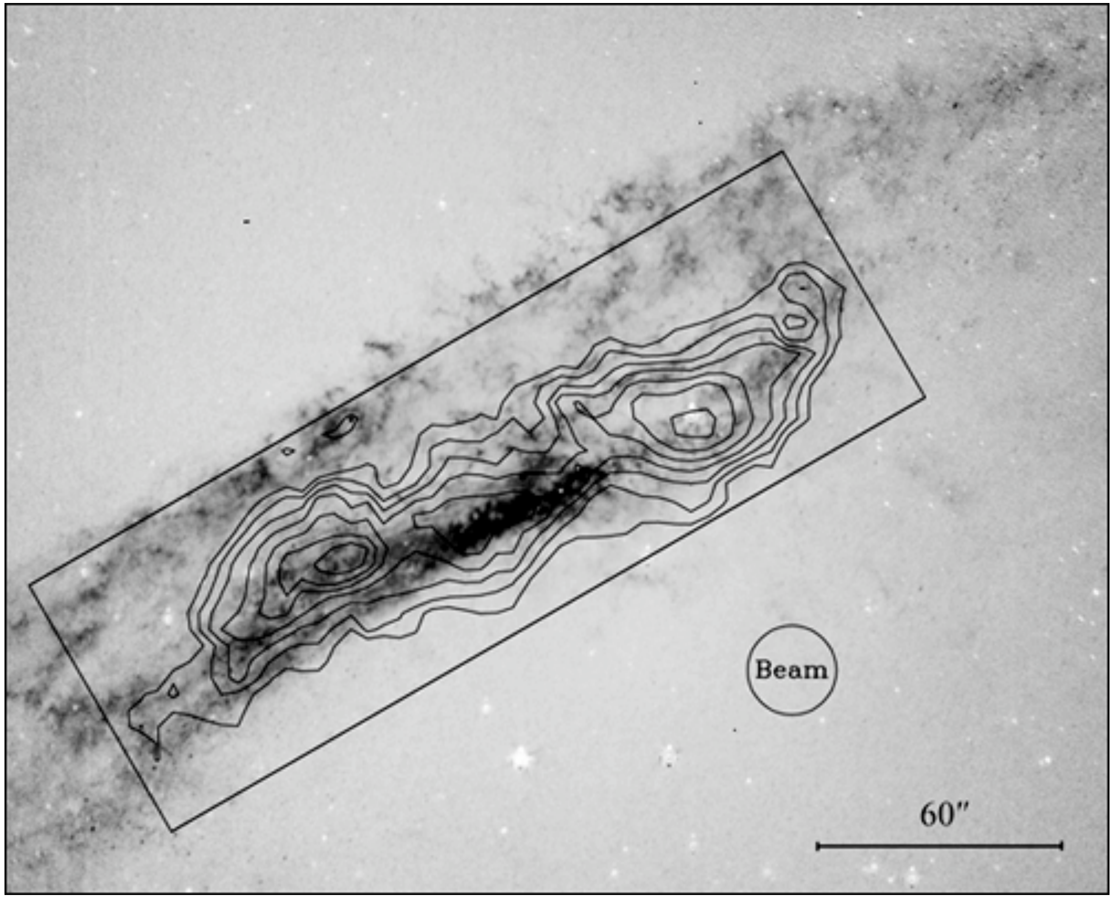
- NIR extinction mapping - 5.2 x 10^9 M_{sun}
- *CO* SEST data (Lundgren 2004) - 4.6 x 10^9 M_{sun}



NGC5128: extinction mapping *vs* CO

The total mass of molecular gas derived using:

- NIR extinction mapping - $4 \times 10^8 M_{sun}$
- *CO* SEST data (Wild 1997) - $10^8 M_{sun}$



Pros & cons

The method's pros:

- high sensitivity
- high spatial resolution (~ few tens of arcsecond)
- independence from the temperature of dust
- traces the densest and coldest cores

… however the results can be dependent on the geometry of a galaxy

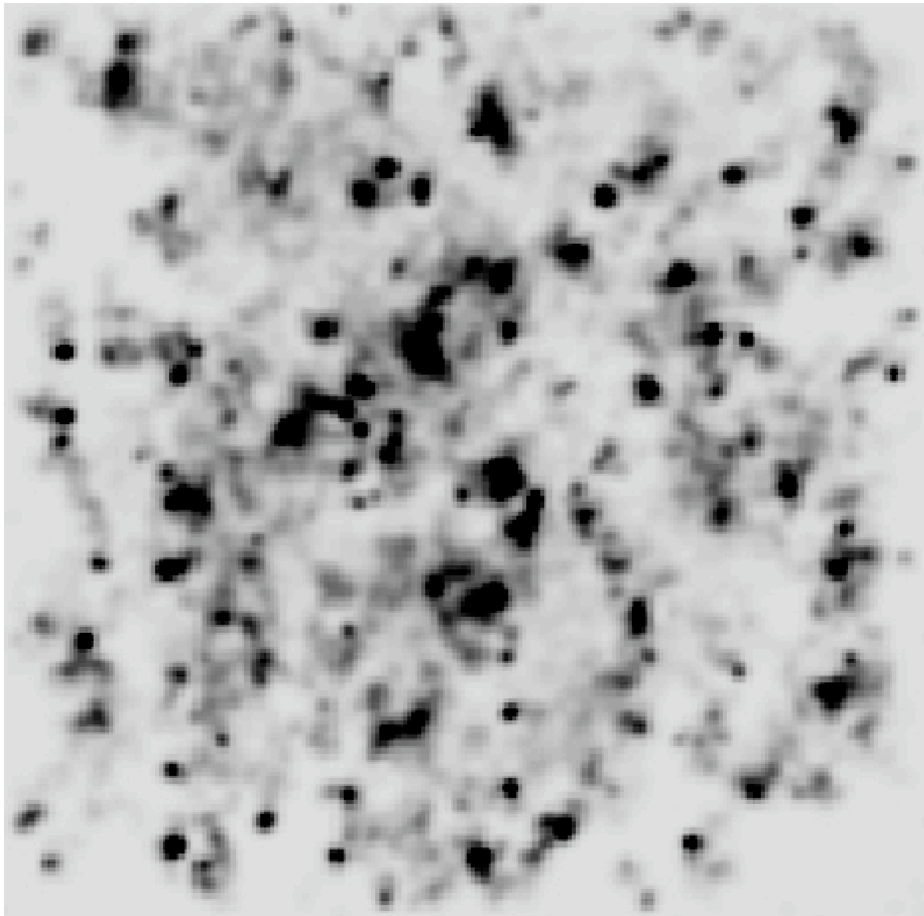
Radiative transfer modeling

3D Monte Carlo code developed by Juvela & Padoan (2003) and Juvela (2005) to compute the flux of the scattered light.

$$L_i = \mathrm{e}^{-z/z_{0,i}^{\mathrm{stars}}}.$$

The H-K and J-H color maps are Computed from the simulated maps at JHK bands.

The original mass function of all generated clouds is selected to be a power law $dN/dM \sim M^{\alpha_{true}}$ with α_{true} = 1.5 . . . 3.

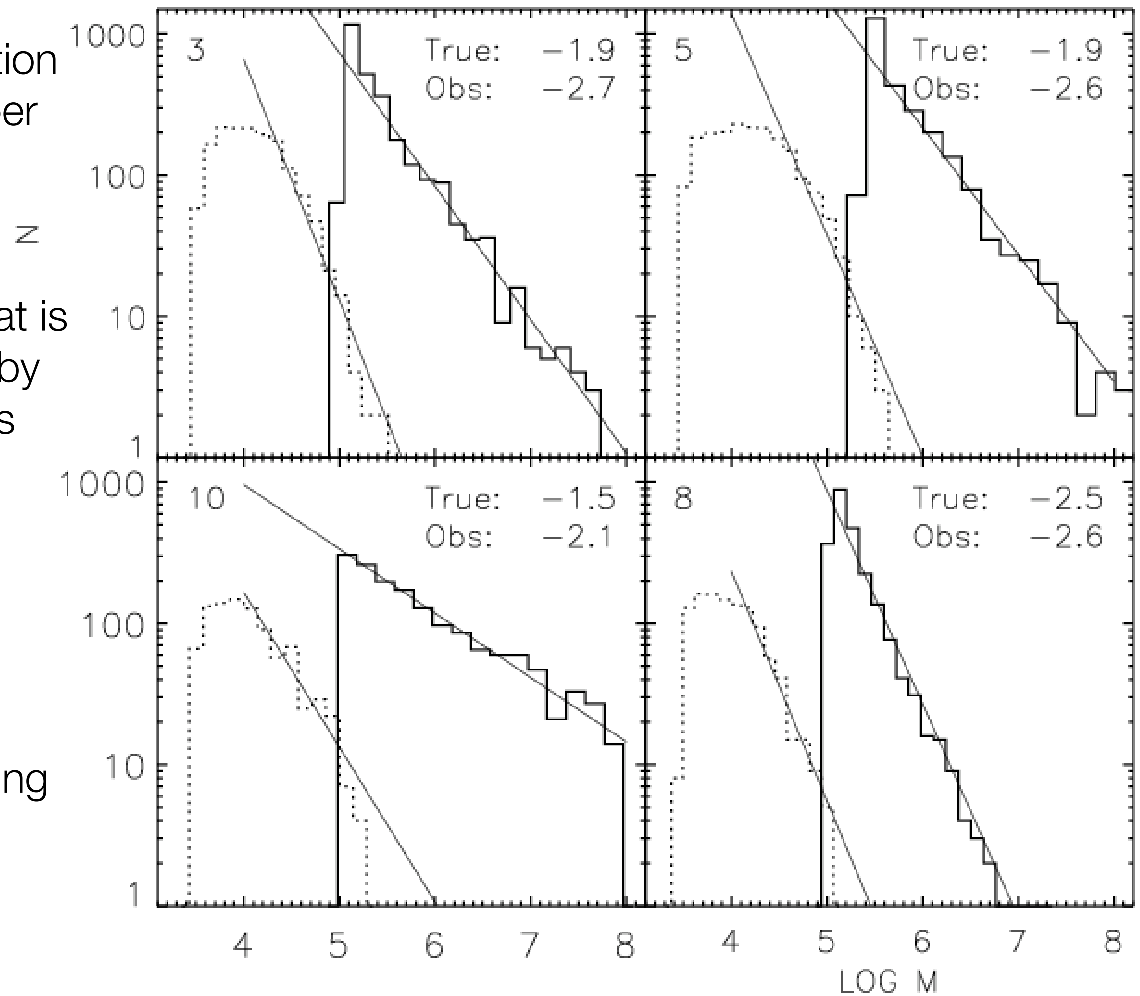


Results of the modeling

- The exact outcome of the simulation ultimately depends on a large number of parameters, the most important being the geometry of the model

- Although the power-law nature that is observed in galaxies is reproduced by the simulations, the observed slopes are systematically different from the true slopes.

- The use of NIR color maps can possibly be complemented with observations in other wavelengths and/or with radiative transfer modeling to improve the estimate of the underlying mass function.



Conclusions

- We offer a new technique of deriving of the total mass of GMCs in a galaxy

- Despite the complexity in the interpretation of color excess the use of color maps to trace GMCs remains interesting due to its superb resolution and the low noise of the column density maps

- GMCs with masses above our completeness limit are described by a power-law distribution

- Characteristics of molecular gas about to start forming stars still not well understood.

- ALMA will be definitely of help