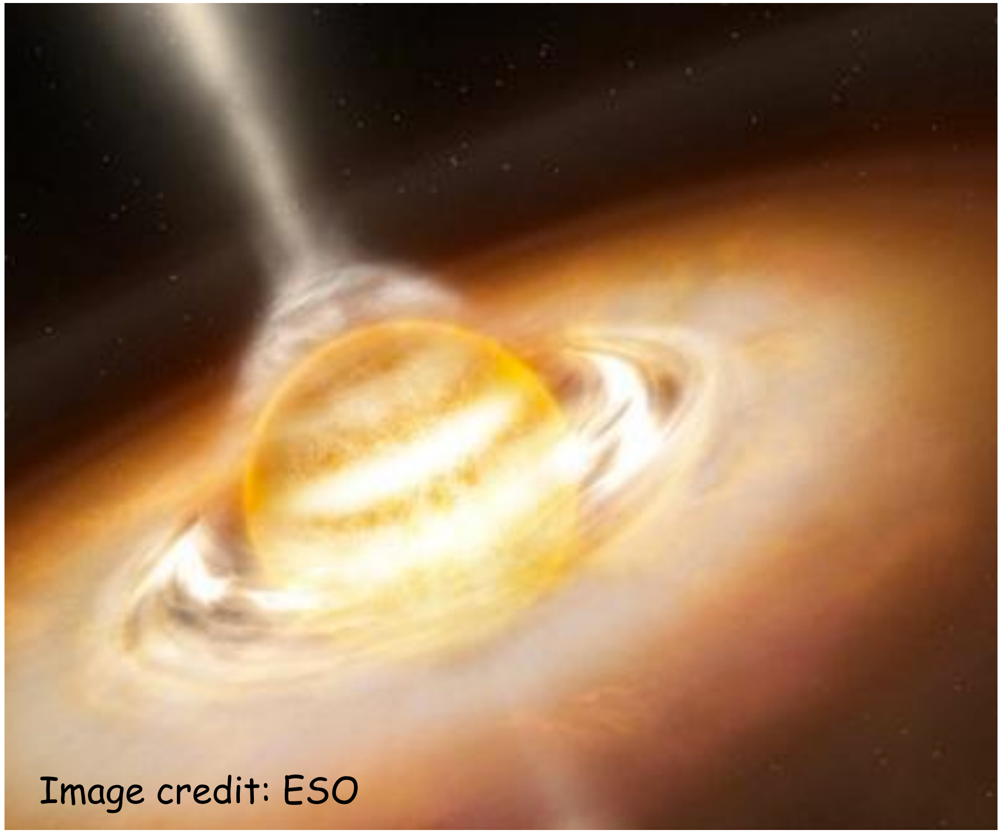


Image credit: ESO

Loredana Spezzi
European Space Agency (ESA-ESTEC)

Early evolution of low mass stars and brown dwarfs: an observational overview

Outline

Part I:

Main results of the Spitzer "Core to disk" and "Gould's Belt" surveys
(PMS stars classification, lifetime, variety of evolved disk)

Part II:

Evolution and mass dependency of the mass accretion rate
(Milky Way vs. Magellanic Clouds)

Part III:

Age spread in young massive clusters (the case of NGC3603)

A "collage" of the work of N. Evans & the c2d Team, L. Allen & the GB team, the WFC3 SOC Team, G. Beccari, G. De Marchi, F. Paresce, N. Panagia and many others.....

Part I: Results of the Spitzer c2d and GB surveys

- Focus on Class I to III objects
- For pre-stellar core and Class 0 see talk by P. Andre'

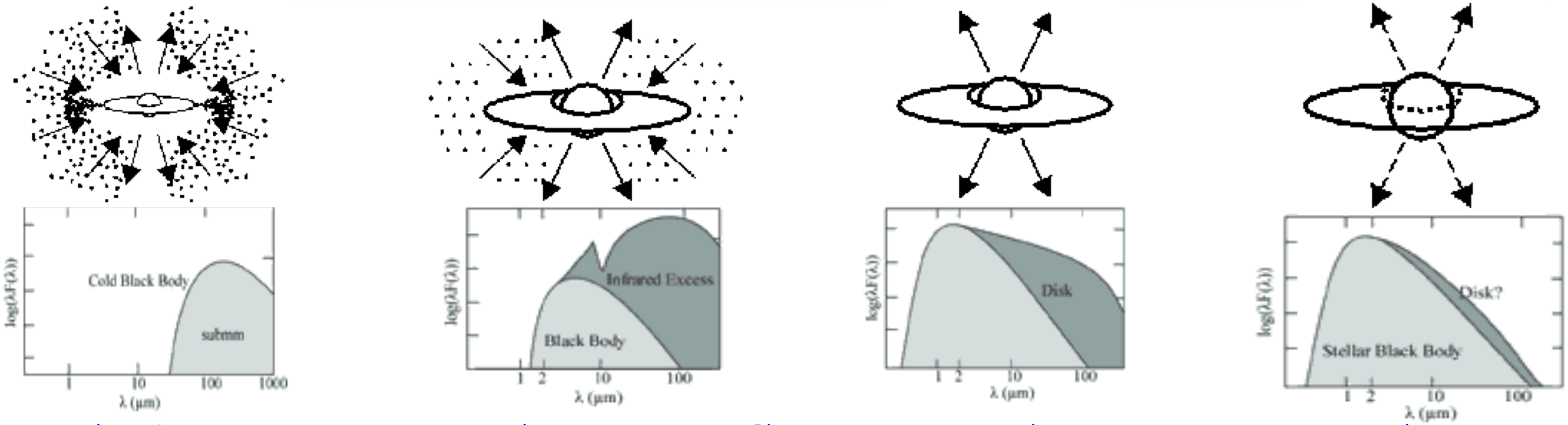
Spitzer c2d and GB surveys

- Observations (IRAC, MIPS, IRS@Spitzer: 3-160μm)
- "Core to disk" (c2d) Survey: Five nearby molecular cloud (Perseus,Ophiuchus,Serpens,Lupus,ChamaeleonII),150 compact molecular cores and ~300 stars in a wide range of evolutionary states
- More clouds were observed in the Gould's Belt (GB) Survey (Musca, Lup V & VI, etc.)
- The five clouds combined contain 1024 YSOs
- There are no more than about 50 (5%) contaminating background galaxies in the sample.
- The sample is complete down to $L_{bol} \approx 0.05\ L_{\odot}$ over a wide range of SED type . With better discrimination against galaxies this limit could be lowered to about $10^{-3}\ L_{\odot}$ (20-30 M_J)
- Appropriate wavelength coverage to study the process of planet formation in disks

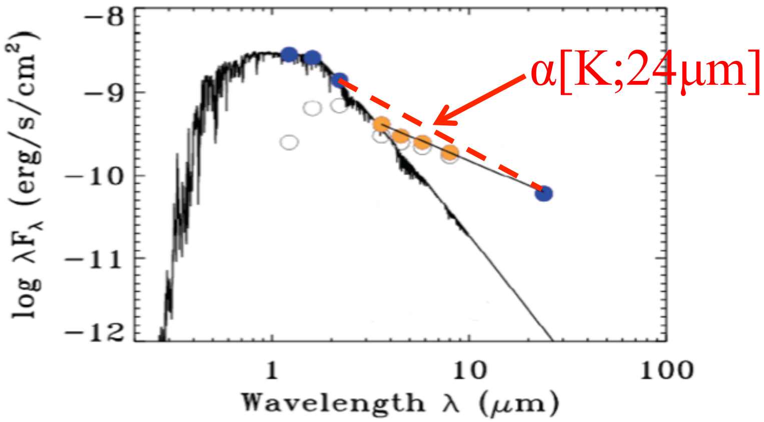
IRAC, MIPS and IRS (3.6 – 70 μm)
Temperatures: 100 to 1500 K
Radii: 0.1–30 AU (size of Neptune's orbit)

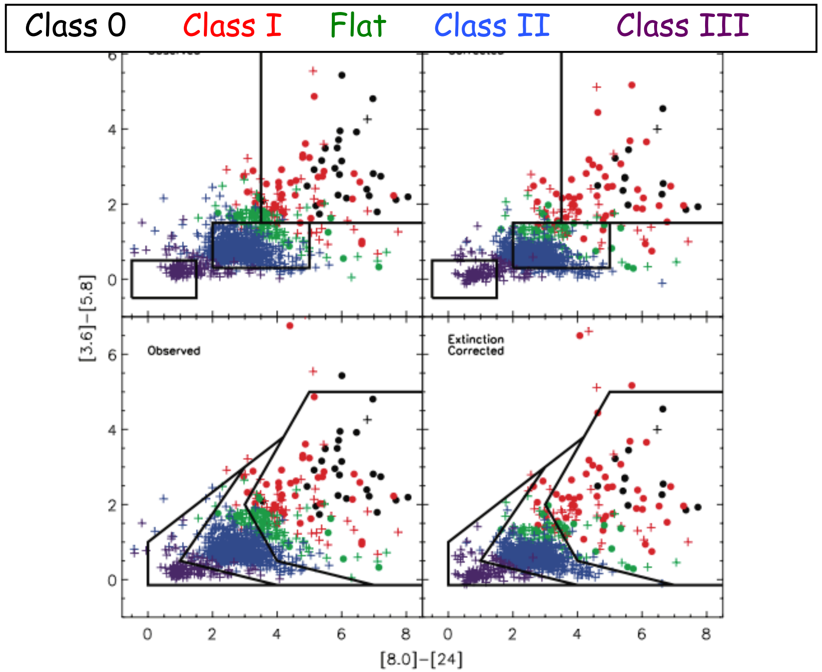
Band	$\lambda_{\rm eff}$	$T_{\rm disk}$	$R_{\rm disk}$ (AU) around a				
	(μm)	(K)	BD	Low-mass	1 $M_{\odot}$	F-type	A-type
J_{2MASS}	1.2	2414	0.001	0.005	0.01	0.04	0.04
H_{2MASS}	1.6	1811	0.002	0.01	0.03	0.09	0.09
$K_{s,2MASS}$	2.1	1379	0.004	0.03	0.08	0.22	0.23
IRAC-1	3.6	804	0.007	0.06	0.15	0.44	0.45
IRAC-2	4.5	643	0.011	0.10	0.24	0.71	0.72
IRAC-3	5.8	499	0.018	0.16	0.39	1.14	1.16
IRAC-4	8.0	362	0.033	0.28	0.69	2.04	2.07
MIPS-1	24.0	120	0.34	2.9	7.2	21.3	21.7
MIPS-2	70.0	41	2.90	25.0	60.9	180	183
MIPS-3	160.0	18	23.70	205	500	1485	1509

PMS star classification



Class 0 Class I Flat Class II Class III





Lada (1987), Greene et al. (1994)

I $0.3 \leqslant \alpha$;

Flat $-0.3 \leqslant \alpha < 0.3$;

II $-1.6 \leqslant \alpha < -0.3$;

III $\alpha < -1.6$.

Chen et al. (1995)

O $T_{\mathrm{bol}} < 70$;

I $70 \leqslant T_{\mathrm{bol}} \leqslant 650$;

II $650 < T_{\mathrm{bol}} \leqslant 2800$.

Muzzerolle et al. 2004, Robitaille et al. 2006

c2d results: IR classes

Percentage without extinction correction:

Class 0/I 16%

Flat 12%

Class II 60%

Class III 12%

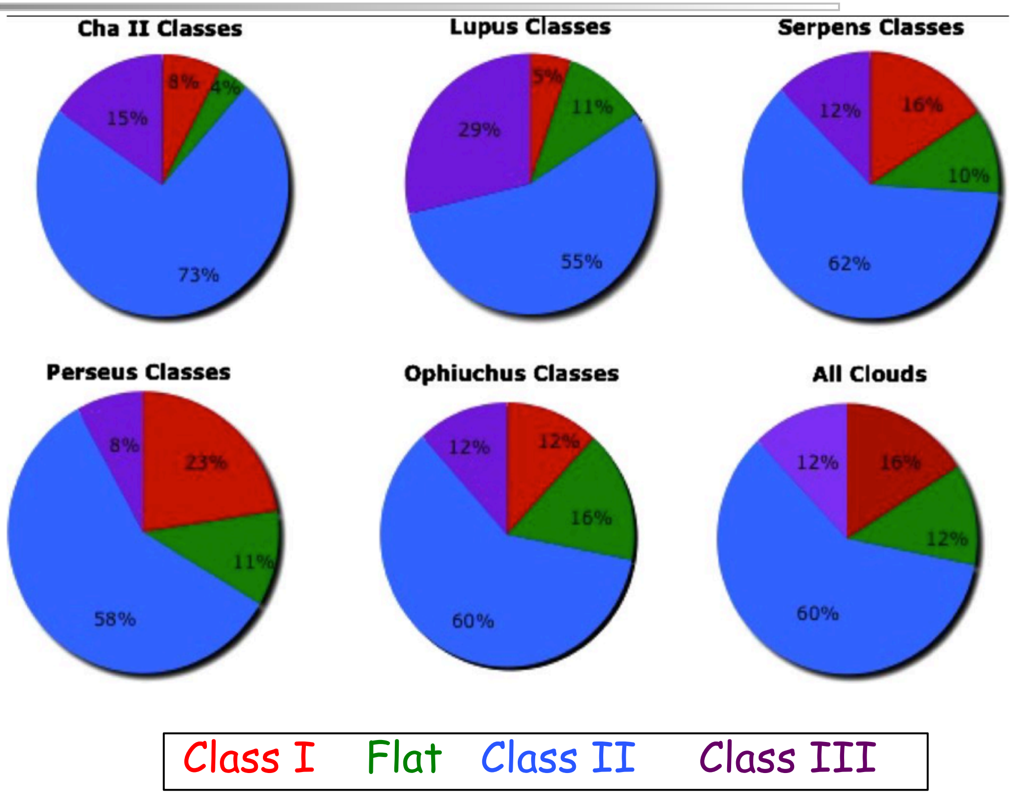
Percentage after extinction correction

Class 0/I 14%

Flat 9%

Class II 64%

Class III 13%



Differences from previous literature

Wilking et al. (1989) who found roughly equal number of Class I and Class II objects in Ophiuchus.

Variations from cloud to cloud

Effects of small number statistics are substantial for Cha II and Lupus.

Perseus stands out as particularly rich in Class I sources.

Evans et al. 2009, ApJ Supp. Ser. 181, 321

The outliers: Lupus V and VI

Total Number of YSO Candidates in the Lupus V and VI Clouds Organized by Lada Class

Lada Class	Lupus I[a]	Lupus III[a]	Lupus IV[a]	Lupus V	Lupus VI	All c2d clouds[b]
I	2 (15%)	2 (3%)	1 (8%)	0	0	165 (16%)
Flat	3 (23%)	6 (9%)	1 (8%)	0	1 (2%)	123 (12%)
II	6 (47%)	41 (59%)	5 (42%)	9 (21%)	5 (11%)	612 (60%)
III	2 (15%)	20 (29%)	5 (42%)	34 (79%)	39 (87%)	124 (12%)
Total	13	69	12	43	45	1024

Why such a high fraction of class III YSOs?

1) Higher fraction of binaries (Monin et al. 2007, Kraus & Ireland 2010, Bouwman et al. 2006): UNLIKELY (more data needed)

2) Disk photoevaporation due to nearby OB stars: UNLIKELY

Few OB star within 0.5 pc

No spatial correlation between disk frequency and position of OB stars

4) Higher characteristic stellar mass: might contribute

Lup V & Lup VI 0.5-0.6 $M_{\odot}$

Other Lup clouds 0.2 $M_{\odot}$

4) Older age: MOST LIKELY (more data needed)

Heiderman et al. 2010: the study SFR vs. gas surface densities for 20 c2d and GB clouds suggests a "threshold" for strong star formation around opticl depth Av = 8 (Onishi et al. 1998; Johnstone et al. 2004; Enoch et al. 2007; Lada et al. 2010; André et al. 2010)

Cloud	Mass above thres.	Fraction of Mass below thres.
Lupus III	95 $M_{\odot}$	90%
Lupus V	0 $M_{\odot}$	100%
Lupus VI	3.8 $M_{\odot}$	99%

The mass above threshold in Lupus V and VI is very small or zero

-> star formation has ceased -> dominance of Class III sources

Spezzi et al. 2011, ApJ 730, 65

c2d results: lifetimes

Method: Lifetimes are estimates as ratios of number counts in each class with respect to class II counts multiplied by the lifetime for Class II

Assumptions:

-Lifetime of Class II = 2 Myrs (possible range 1.5-3 Myr, see talk by I. Baraffe)

-star formation has been continuous over a period longer than the age of Class II sources

-we can average all our clouds

-all objects of all masses behave identically

the region, such as turbulence, etc).

Number of YSOs by Cloud and Class

Cloud	I	Flat	II	III	$t(I)$ (Myr)	$t(F)$ (Myr)
Cha II	2	1	19	4	0.21	0.11
Lupus[a]	5	10	52	27	0.19	0.38
Perseus	87	42	225	31	0.77	0.37
Serpens	36	23	140	28	0.51	0.33
Ophiuchus	35	47	176	34	0.40	0.53
Total	165	123	612	124	0.54	0.40
After E.C.[b]					$t'(I)$	$t'(F)$
Cha II	1	2	18	5	0.11	0.22
Lupus[a]	5	7	54	28	0.19	0.26
Perseus	76	35	244	30	0.62	0.29
Serpens	32	22	140	33	0.46	0.31
Ophiuchus	27	44	179	42	0.30	0.49
Total	141	110	635	138	0.44	0.35

Average lifetimes before and after extinction correction:

Class 0	0.16 Myr	-	0.10 Myr
Class I	0.54 Myr	-	0.44 Myr
Flat	0.40 Myr	-	0.35 Myr

Previous estimates: 0.01 My for Class 0 (Andre' et al. 1993), 0.1-0.2 for Class I/Flat (Keynon & Hartmann 1995), 0.39 Myr for Class I by (Wilking et al. 1989), 0.25-0.67 Myr (Hatchell et al. 2007)

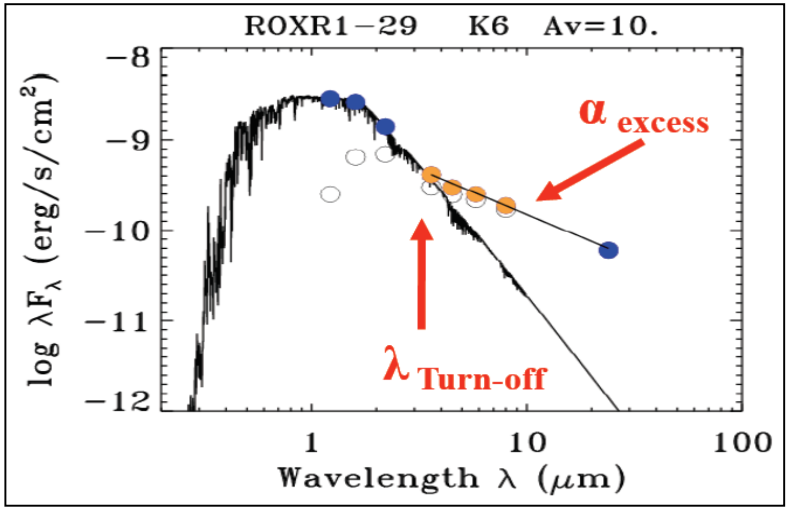
Waiting for GB result for cancellation/better estimate of assumption effects….

The traditional evolution from Class II to Class III does not capture the diversity in SEDs found in the c2d survey (Merin et al., in preparation)

Evans et al. 2009, ApJ Supp. Ser. 181, 321

New SED classification schemes

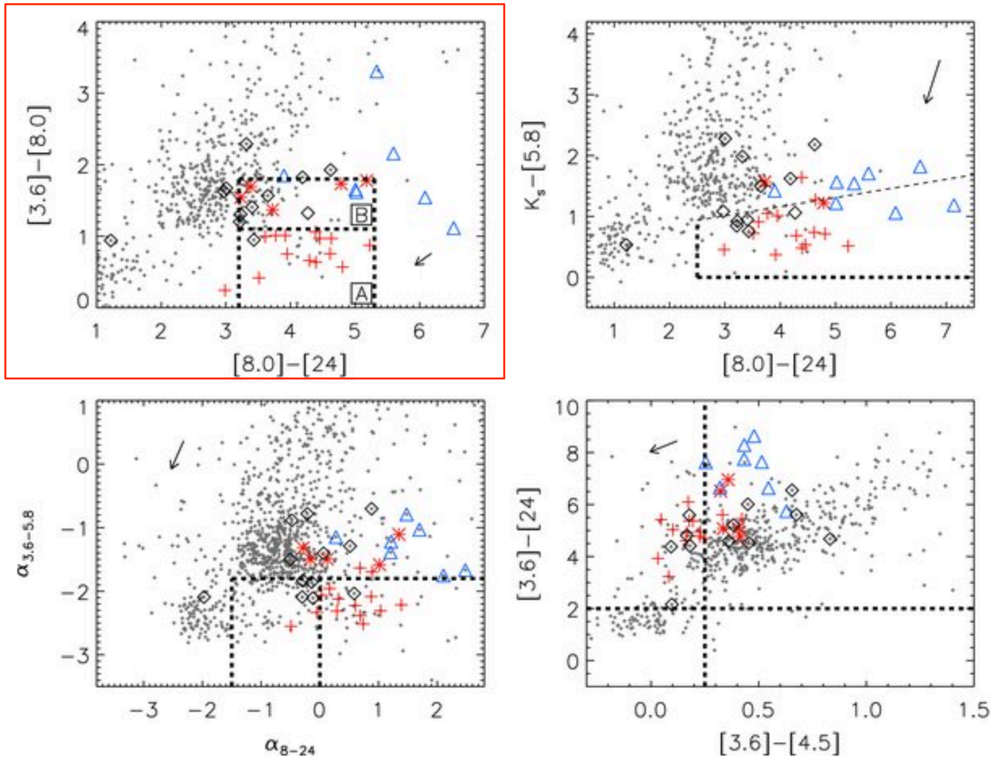
Merin et al., in preparation



- $\lambda_{turn\text{-}off}$ is the last photospheric wavelength in μm
- α_{excess} is the SED slope in $\lambda \cdot F_\lambda$ long-ward than $\lambda_{turn\text{-}off}$

More detailed description of the inner disks !

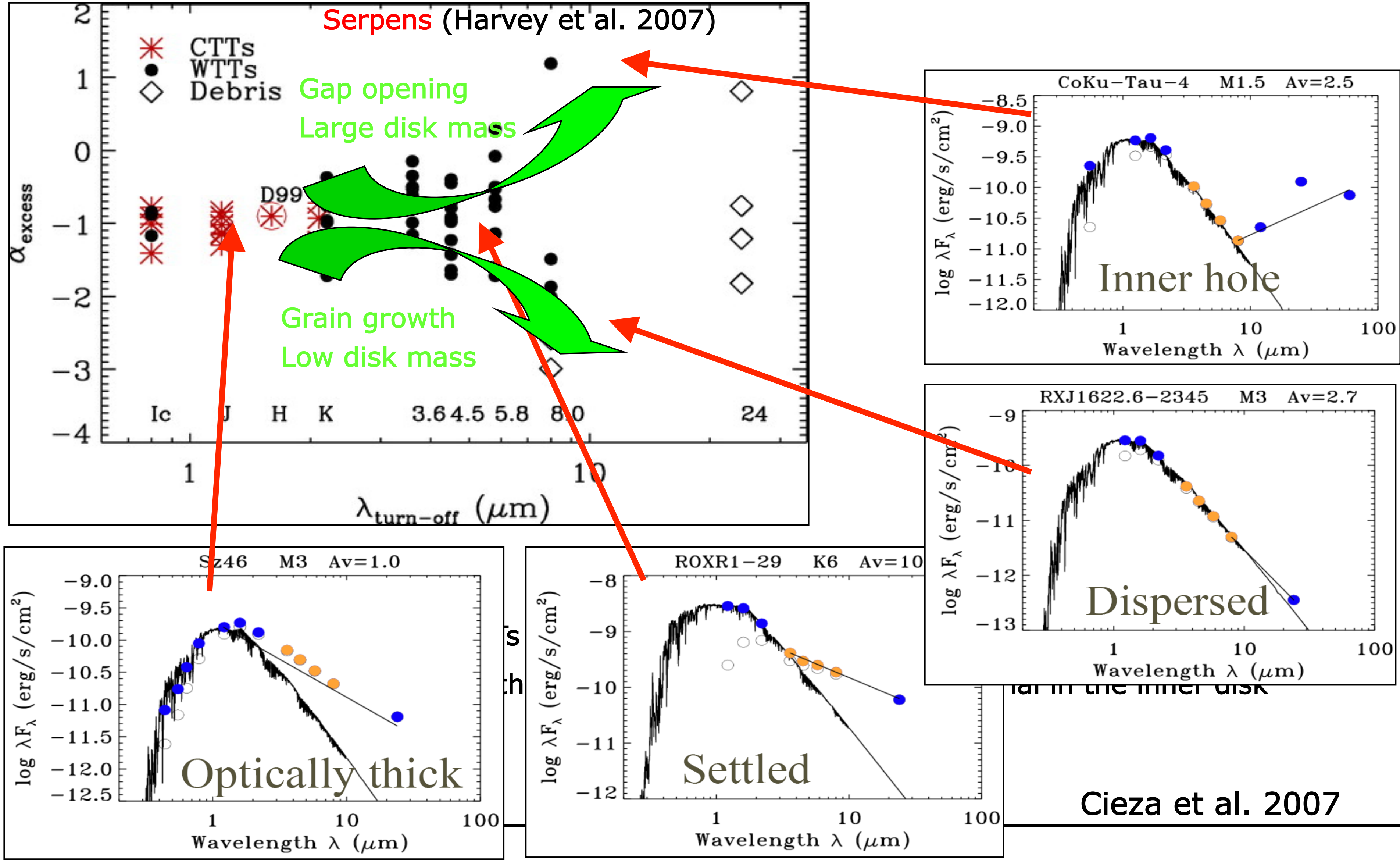
Merin et al. 2010, ApJ 718, 1200



Top-right: Fang et al. (2009)
Bottom-left: Muzerolle et al. (2010)
Bottom right: Cieza et al. (2010)

Better selection for "cold" disk!

…………and the distribution of evolutionary stages suggests different possible evolutionary paths from CTTs to WTTs and Debris disks !



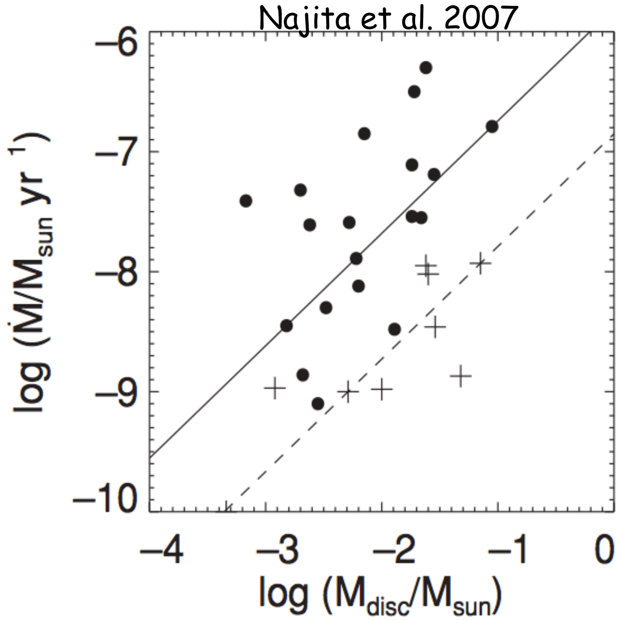
Cieza et al. 2007

c2d "cold" disks (Merin et al. 2010, ApJ 718, 1200)

Sample:

➢15 disk with inner hole from c2d: Optical spectra, 2MASS, and Spitzer photometry, millimeter continuum observations, and IRS 5-35 μm spectra

➢Samples by Brown et al. (2007) and Kim et al. (2009)



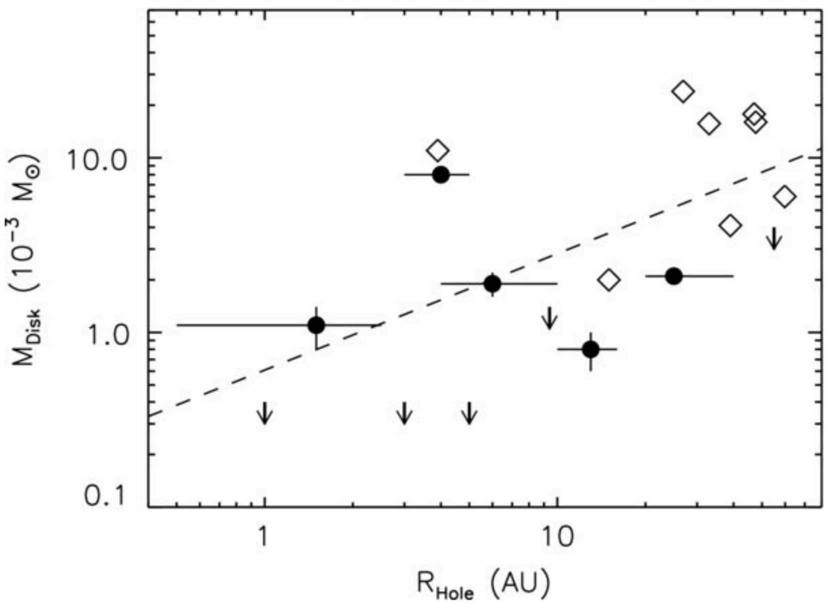
Results:

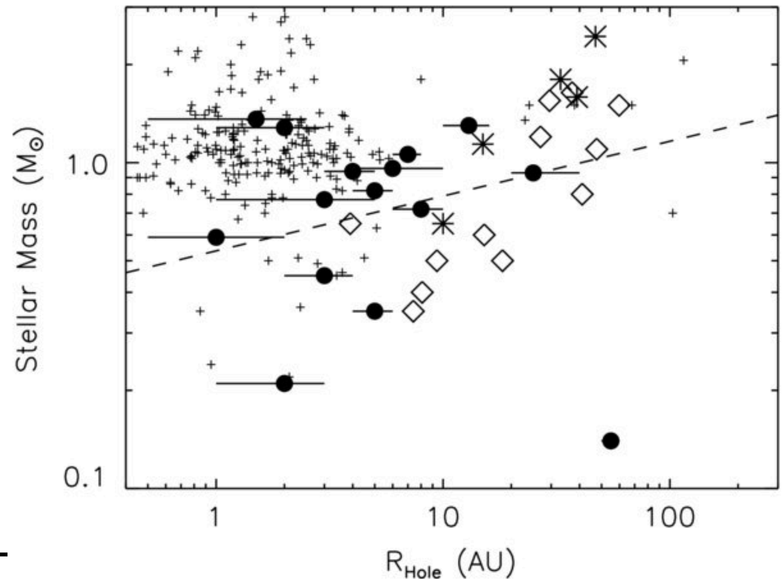
1) A large fraction (75%) of the cold disks are accreting, suggesting that gas is flowing through the dust depleted hole.

2) More massive disks tend to have larger holes.

3)The sizes of the inner holes scale linearly with the stellar mass.

Hole sizes in the c2d sample are generally in better agreement with exoplanet orbit radii (http://exoplanet.eu) .





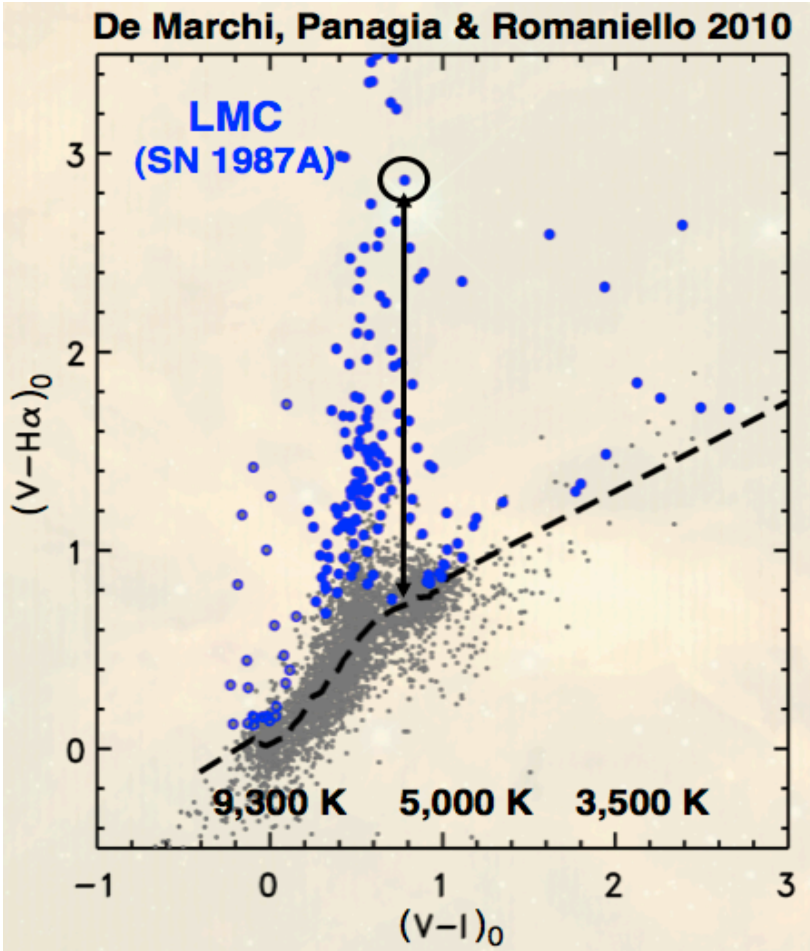
Part II: Mass accretion rates

Milky Way vs. Magellanic Clouds

Photometric determination of the mass accretion rate

$$\Delta H\alpha = (V - H\alpha)^{obs} - (V - H\alpha)^{ref}$$

$L_{H\alpha}$



- **H_α luminosity $L_{H\alpha}$ gives accretion luminosity L_{acc} via relationship calibrated using spectroscopic data** (e.g. Dahm 2008)

$$\mathrm{Log}\,(L_{acc}) = \mathrm{Log}\,(L_{H\alpha}) + (1.72 \pm 0.47)$$

- **Mass, radius and age from PMS isochrones in HR diagram**

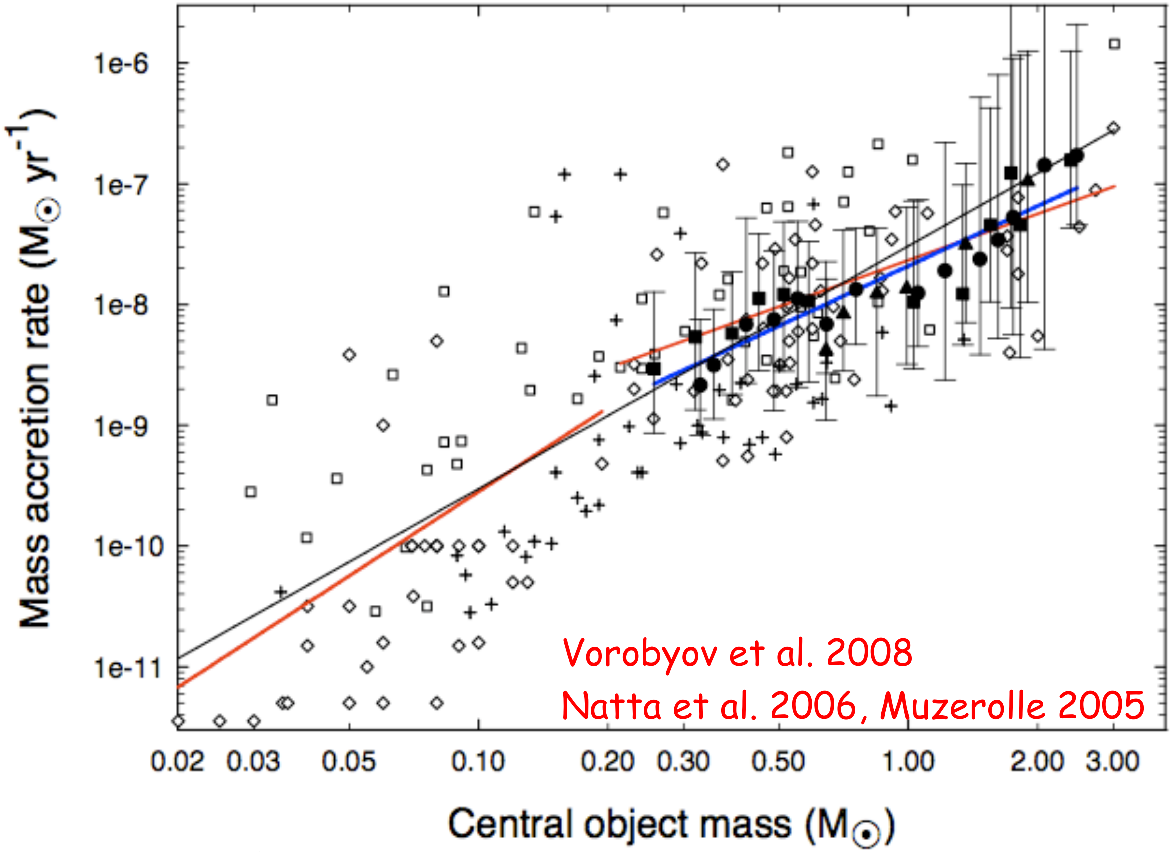
- **Free fall equation gives mass accretion rate *Macc***

$$L_{acc} \simeq \frac{G M_* \dot{M}}{R_*}\left(1 - \frac{R_*}{R_{in}}\right)$$

- **We can study the mass accretion process in distant galactic and extra-galactic star-forming regions for very large PMS star samples using HST.**

See talk by G. De Marchi

Mass accretion rate vs. stellar mass



$$\dot{M} \propto M_*^2 \quad 0.04 < M_* / M_\Theta < 5$$

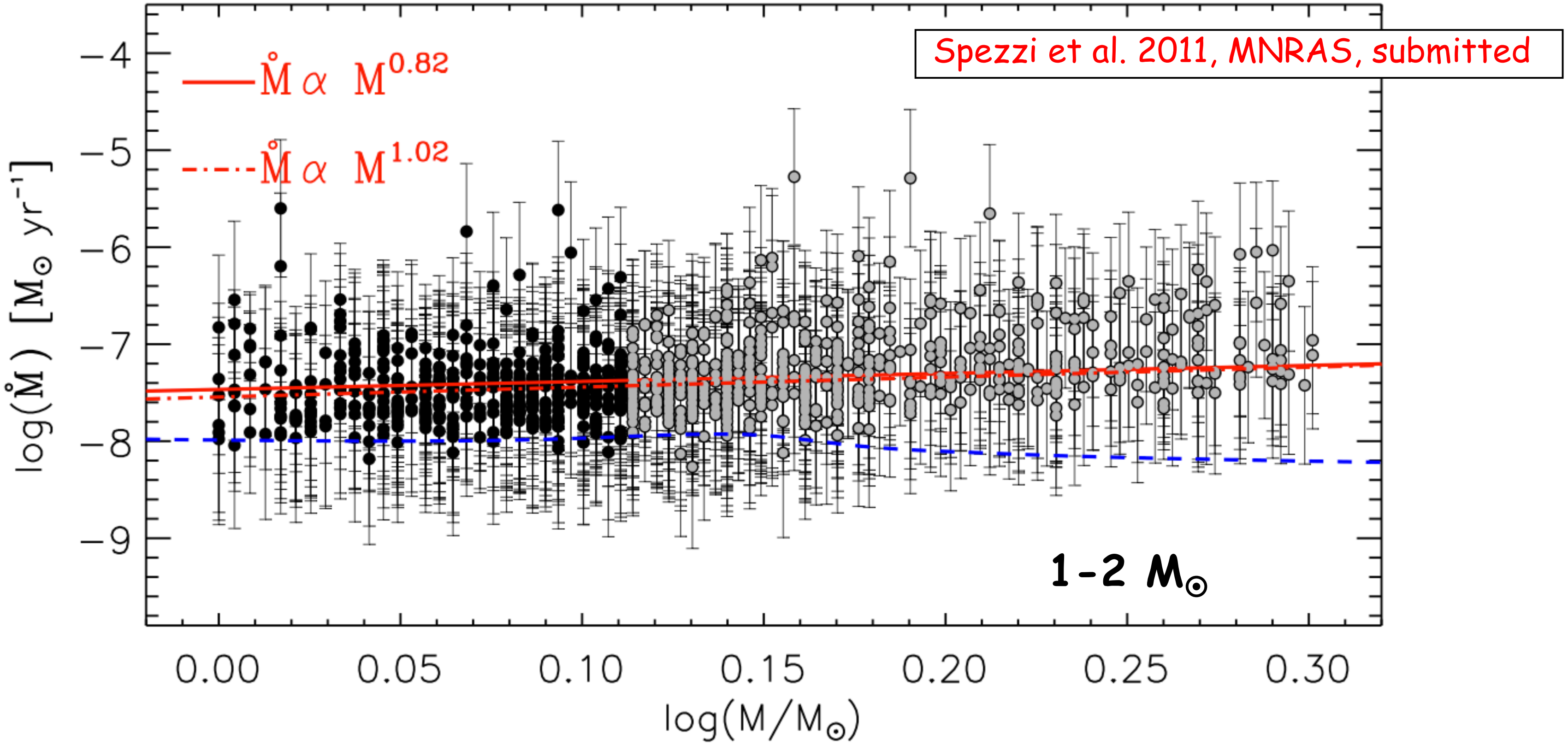
$$\dot{M} \propto M_*^3 \quad M_* / M_\Theta < 0.1$$

$$\boxed{\dot{M} \propto M_*^{1.1} \quad 0.2 < M_* / M_\Theta < 2}$$

IPHAS survey of IC1396
(Barentsen et al. 2011)

See talks by Alcala', De Marchi, Hartmann, Manara, Natta

Mass accretion rate vs. stellar mass in the LMC



$\dot{M} \propto M_*^2 \quad 0.04 < M_*/M_\Theta < 5$

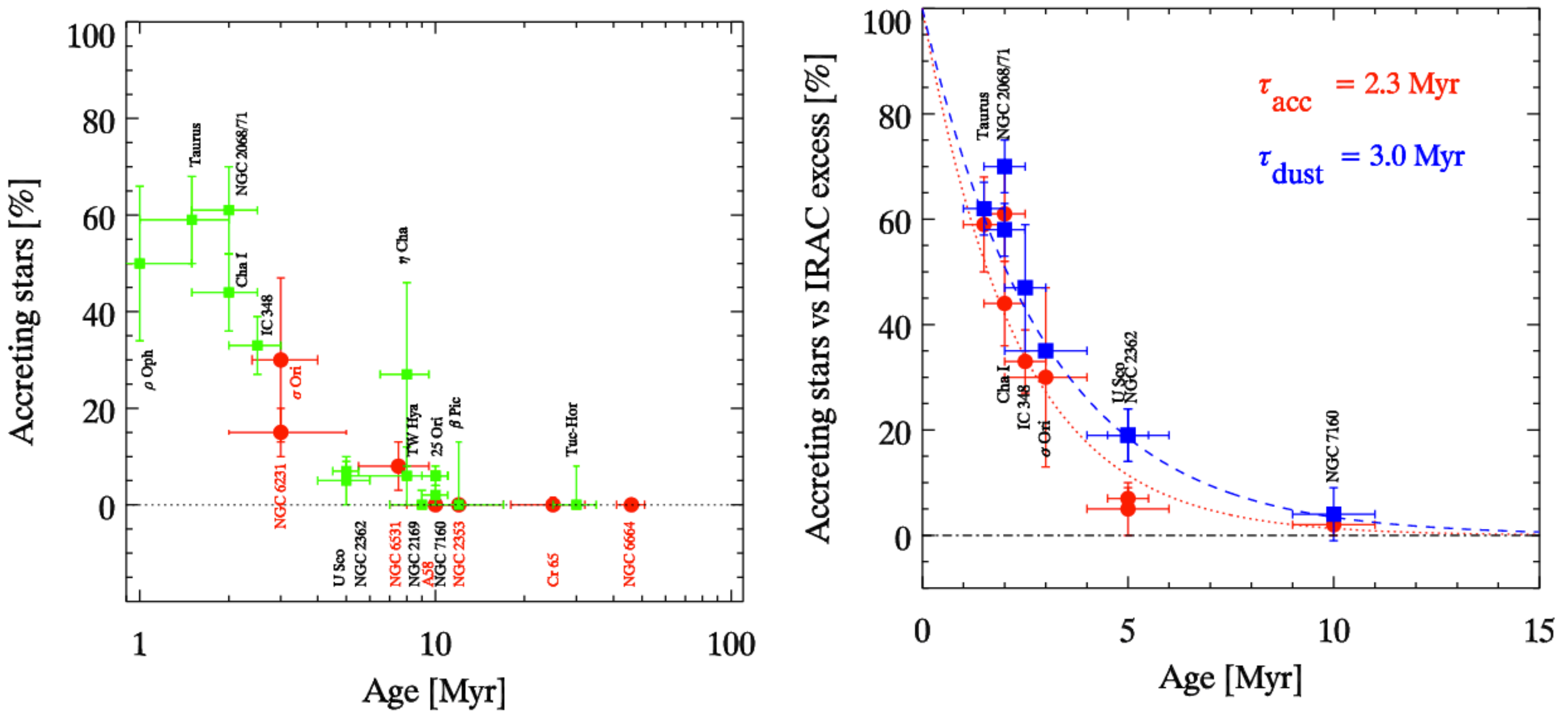
$\dot{M} \propto M_*^3 \quad M_*/M_\Theta < 0.1$

$\boxed{\dot{M} \propto M_*^{1.1} \quad 0.2 < M_*/M_\Theta < 2}$ → IC1396 (Barentsen et al. 2011)

Timescale of mass accretion and IR excess in the MW

-Observational evidences point to many process taking place in young disks: disappearance of the inner hot dust, dust crystallization, radial mixing, transition from flared to flat geometry, etc

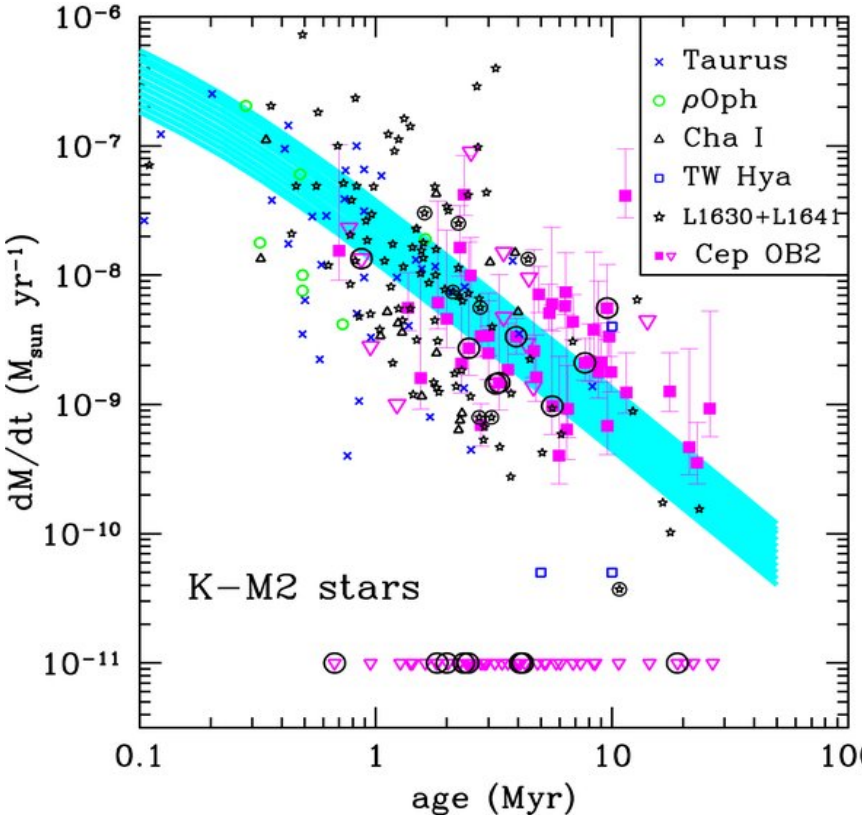
-The inner disks disappear at a constant rate from 1 to 10 Myr.



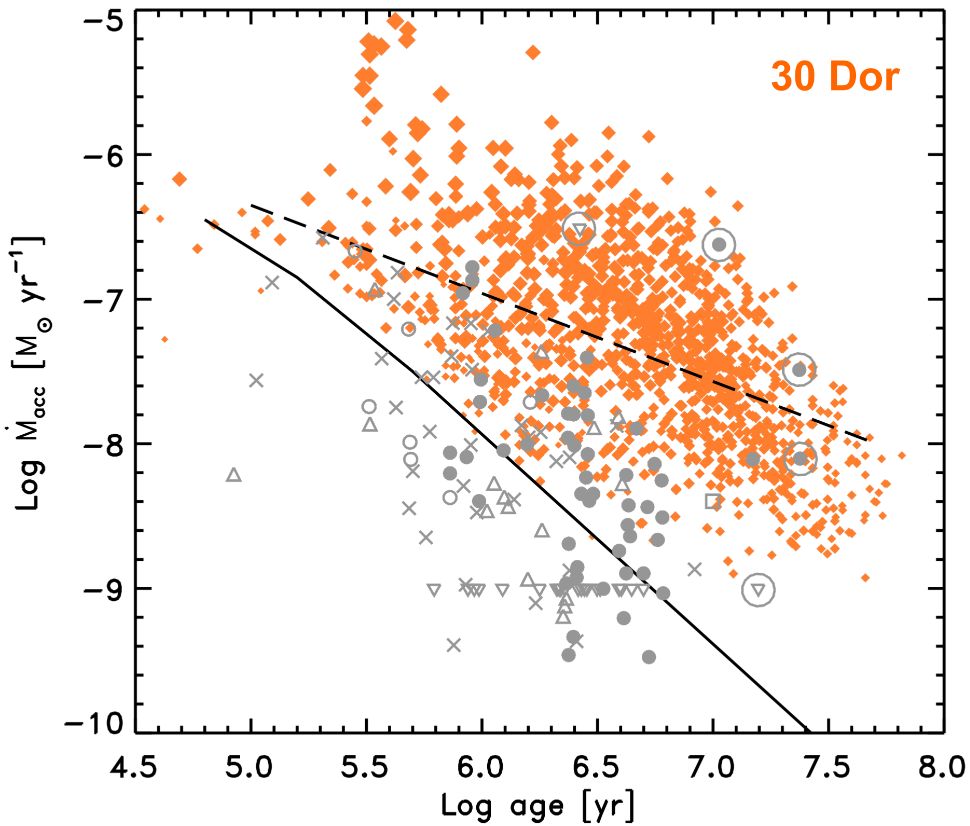
- Sample: PMS stars in the spectral type range K0-M5, ages between 1-30 Myr.
- The mass accretion appears to cease (or drop below detectable level) earlier than the dust is dissipated in the inner disk.
- Assuming an exponential decay, the mass accretion timescale is 2.3 Myr, compared to a near-to-mid IR excess timescale of 3 Myr.

Fedele et al. 2010, A&A 510, 7

Mass accretion rate evolution: MW vs. MCs



Adapted from Sicilia-Aguilar et al. 2006, 2010



De Marchi et al, 2011

See talks by Hartmann, De Marchi

Mass accretion rate evolution: samples in the range 1-2 $M_\odot$

Milky Way

Galactic region	Typical Age (Myr)	Median log $\dot{M}$ ($M_\odot$/yr)	Number of members with $1 \leqslant M/M_\odot \leqslant 2$	Ref.
ρ-Ophiuchus† (ρ-Oph)	0.5	-7.95	4	Natta et al. (2006)
Orion Nebula Cluster (ONC-young) Orion Nebula Cluster (ONC-old)‡	3 12	-7.60 -9.00	9 9	Panagia et al. 2011 (in preparation)
IC 348 Lupus III (LupIII) σ-Orionis (σ-Ori) Taurus (Tau)	2-3	-7.81	9	Dahm (2008) Herczeg & Hillenbrand (2008) Rigliaco et al. (2011) Calvet et al. (2004)
Trumpler 37 (Tr37) Chamaeleon II (ChaII)	4	-9.49	88	Sicilia-Aguilar et al. (2006, 2010); Barentsen et al. (2011) Spezzi et al. (2008)
η-Chamaeleontis (η-Cha) Orion OB 1c Association (Ori-OB1c) λ-Orionis (λ-Ori)	5-7	-8.98	7	Jayawardhana et al. (2006) Calvet et al. (2004) Calvet et al. (2004)
Hydrae (Hya)	8-10	-10.52	4	Pinzón et al. (2007); Jayawardhana et al. (2006)
β-Pictoris (β-Pic) NGC 7160	12	-10.26	5	Pinzón et al. (2007); Sicilia-Aguilar et al. (2010) Sicilia-Aguilar et al. (2010)
Lower Centaurus Crux (LCC) Upper Centaurus Lupus (UCL)	16	-8.32	40	Pinzón et al. (2007) Pinzón et al. (2007)
Tucana-Horologium (Tuc-Hor)	30	-11.03	8	Pinzón et al. (2007); Jayawardhana et al. (2006)

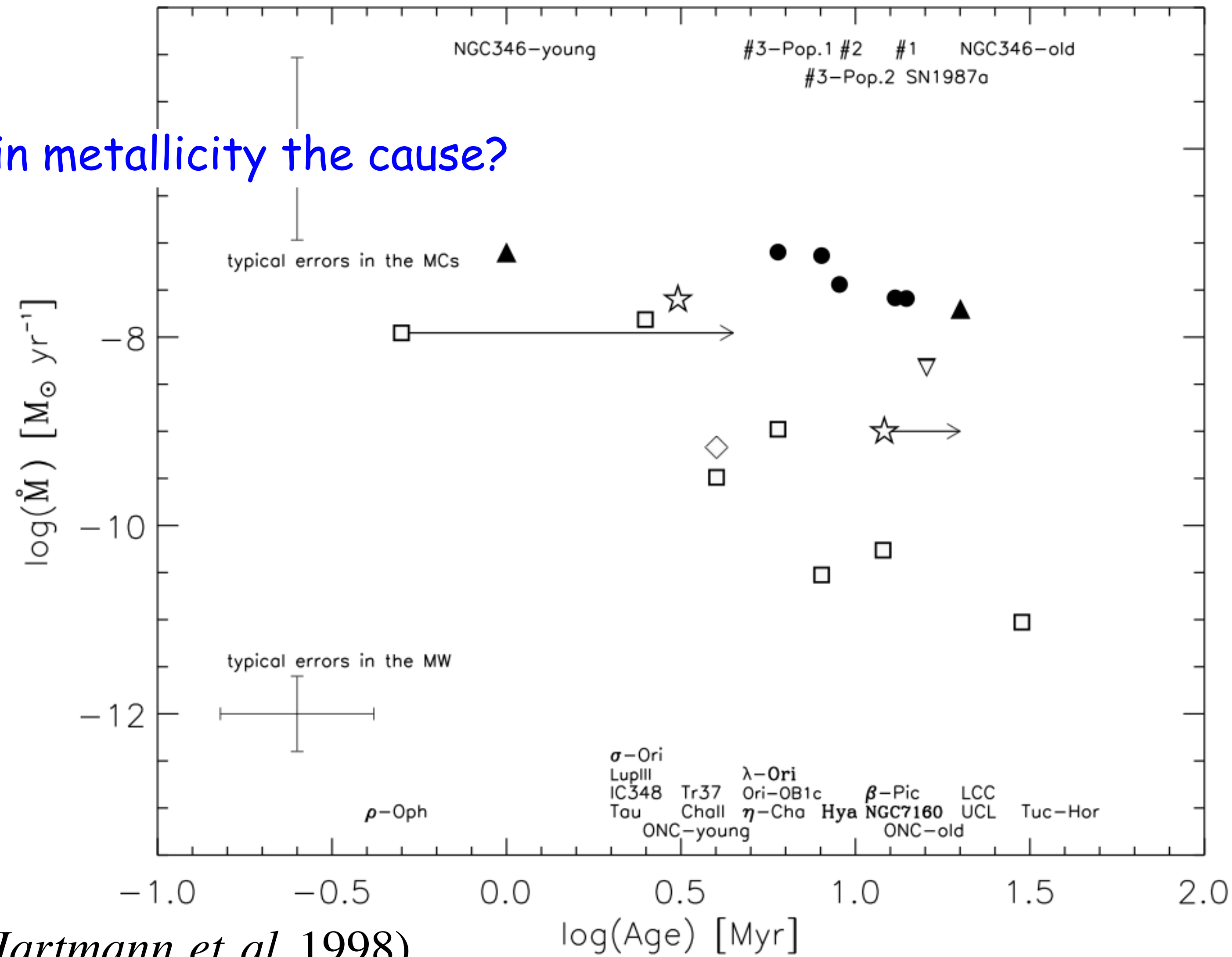
Magellanic Clouds

MC region	Typical Age (Myr)	Median logM ($M_\odot$/yr)	Number of member with $1 \leq M/M_\odot \leq 2$	Ref.
LMC #1	13	-7.6	490	Spezzi et al. 2011
LMC #2	9	-7.4	325	Spezzi et al. 2011
LMC #3-Pop.1	8	-7.1	96	Spezzi et al. 2011
LMC #3 Pop.2	6	-7.2	146	Spezzi et al. 2011
SN1987A	14	-7.6	104	De Marchi et al. 2010
NCG346-young (SMC)	1	-7.1	350	De Marchi et al. 2011
NCG346-old (SMC)	20	-7.7	330	De Marchi et al. 2011

Mass accretion rate evolution: MW vs. MCs (mass range 1-2 $M_\odot$)

Spezzi et al. 2011, MNRAS, submitted

Is the difference in metallicity the cause?



$$\dot{M} \propto t^{-\eta}$$

$$\eta_{MCs} = 2.15 \pm 0.22$$

$$\eta_{MW} = 2.89 \pm 0.72$$

$$\eta_{viscous} = 1.4 - 2.8 \quad (Hartmann\ et\ al.\ 1998)$$

Part III: Age spread in young massive clusters

The case of NGC3603 and more…

See talks by De Marchi

Larger age spread in young massive clusters: the case of NGC3603

Right Ascension: $11^h\,15^m\,7^s$

Declination: $-61^{\circ}\,15'\,30''$

Distance: 7 ± 1 kpc

See poster by G. Beccari

Type: Galactic star-burst cluster

Total Mass: $\sim10^4\ M_\odot$

Previous age estimates: 1-3 Myr ? But…

The blue supergiant Sher25 is 10 Myr old and many other blue supergiants appear associated with this cluster

Proper motion studies indicate a second population with age ~4-5 Myr

Bolometric luminosity:

100 times that of Orion

0.1 times that of 30 Doradus

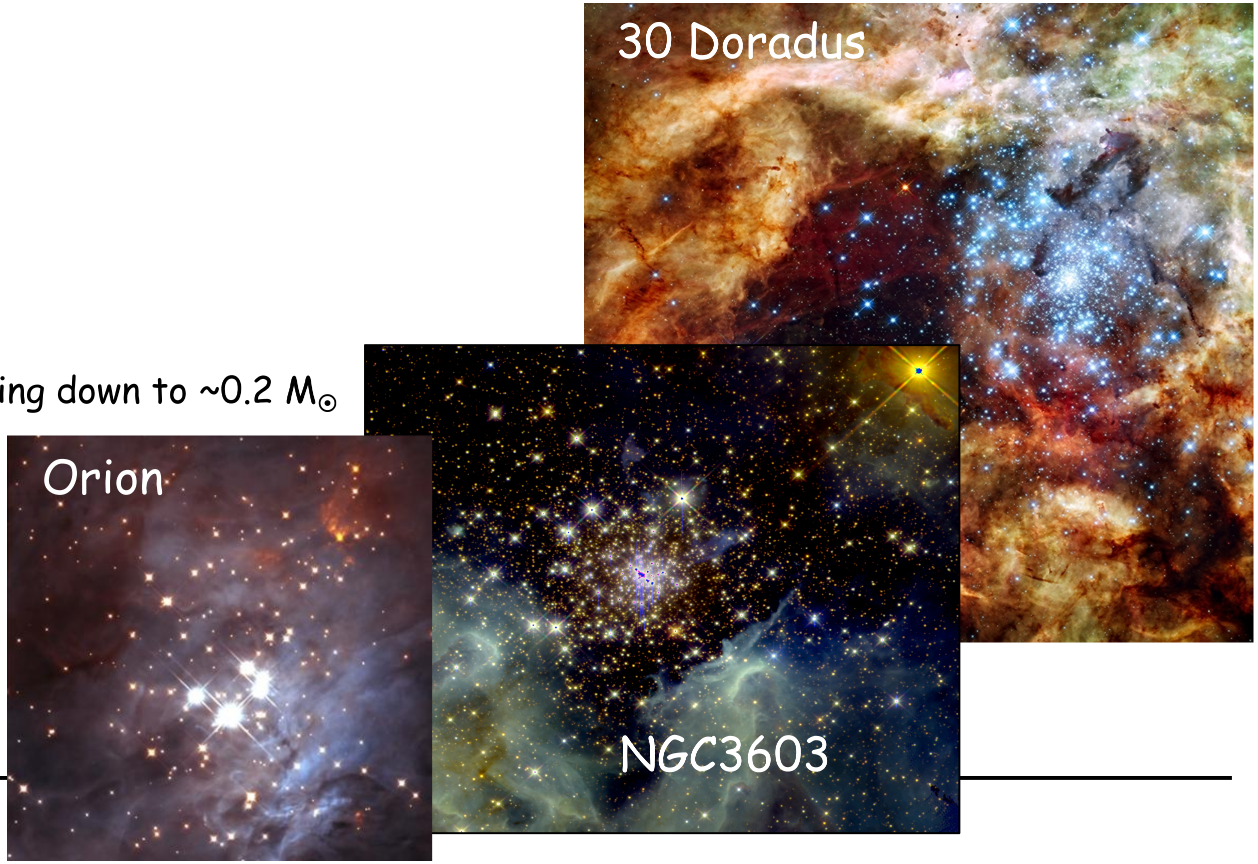
Stellar content:

3 Wolf-Rayet stars

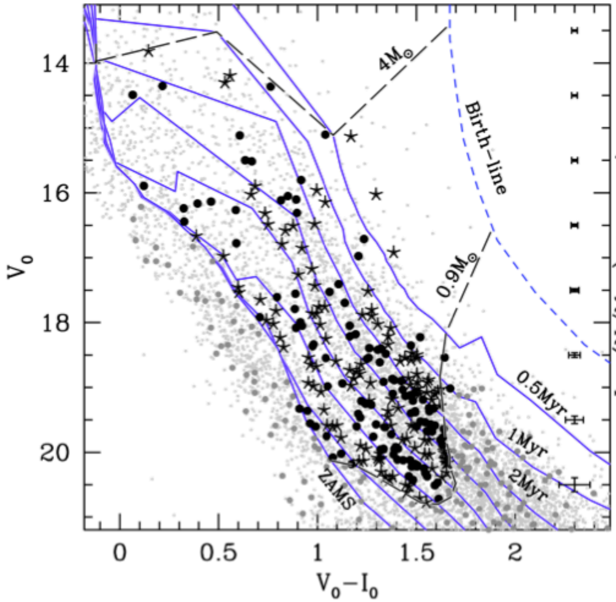
6 O3-type stars

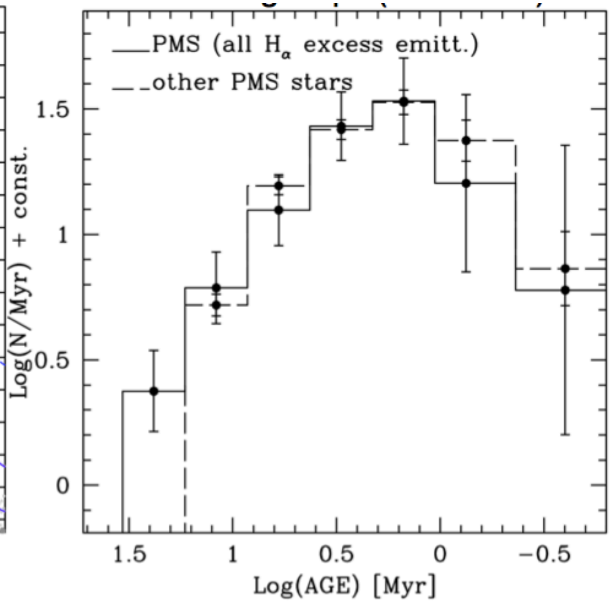
numerous late O-type stars

present day known mass function extending down to $\sim0.2\ M_\odot$



Ongoing star formation for at least 10-30 Myrs



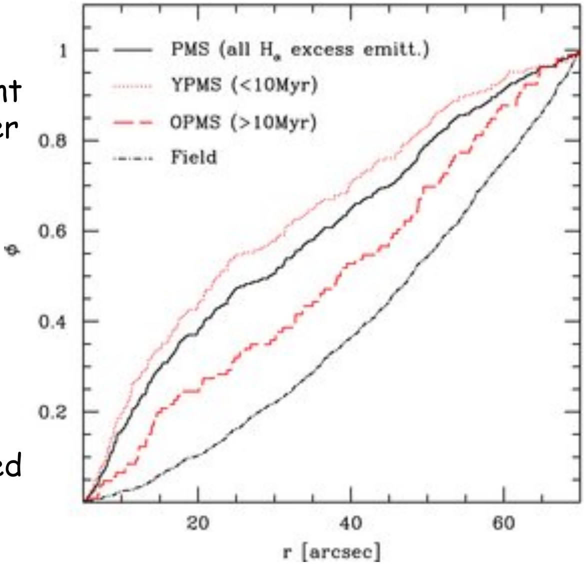


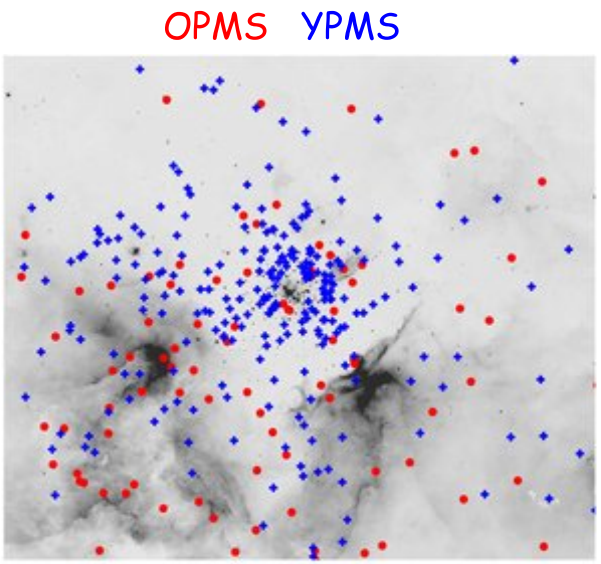
No gaps in age are evident
-> star formation has been ongoing for 10-30 Myr

- The YPMS and OPMS populations have different spatial distributions with respect to the cluster center

- The radial distributions of both the YPMS and OPMS are different from the field population
-> they both belong to NGC3603

- The YPMS population is more centrally concentrated than the field stars -> the YPMS is younger





See poster by G. Beccari

IS

NGC3603 is not a unique case

There is evidences of multiple star formation in:

30 Doradus (LMC; De Marchi et al., 2011)
M16 (Eagle Nebula, De marchi et al. 2011)
NGC602 (SMC; Beccari et al., submitted)
NGC346 (Small Magellanic Cloud; De Marchi et al. 2011)
LH95 (LMC, Da Rio et al. 2010)
Sandage 96 (NGC2403; Vinko' et al. 2009)
Age spread of 300 Myr in other LMC clusters (Milone et al. 2009)
Multiple stellar population of galactic GCs (Piotto 2008, Lee et al. 2009)

Is continuous generation of stars the dominant mechanism of star formation?
We might need to revise the assumption that clusters are simple coeval stellar populations!

Open issues: how can we help?

Part I: connection between SED variety and disk dissipation mechanisms

Herschel & ALMA (follow-up spectroscopy of Spitzer c2d abd GB surveys)

Part II: Why the typical mass accretion rate of young stars in the MCs appear higher than in their galactic counterpart?

Spectroscopy of roughly solar mass stars in the MCs will be possible only with JWST or E-ELT

Some attempt with Xshooter (S. Randich et al.)

GAIA

Part III: Do we need to revise the assumption that clusters are simple coeval stellar populations?

GAIA will help with:

-Better constraints on the distance and kinematics/membership of SFRs

-Better age/mass estimates

-Reducing the uncertainty in the typical M_{acc}

-Better PMS evolutionary models thanks to the Gaia galactic dataset

Disk variety: togliere

Class 0 | Class I | Flat | Class II | Class III

Primordial disks
- thick
- gas-rich, accreting
- protoplanetary

Cold disks
- flux density ratio $S_\nu(30\mu m)/S_\nu(13\mu m)>5$
- inner holes or wide gaps with little dust
- might accrete

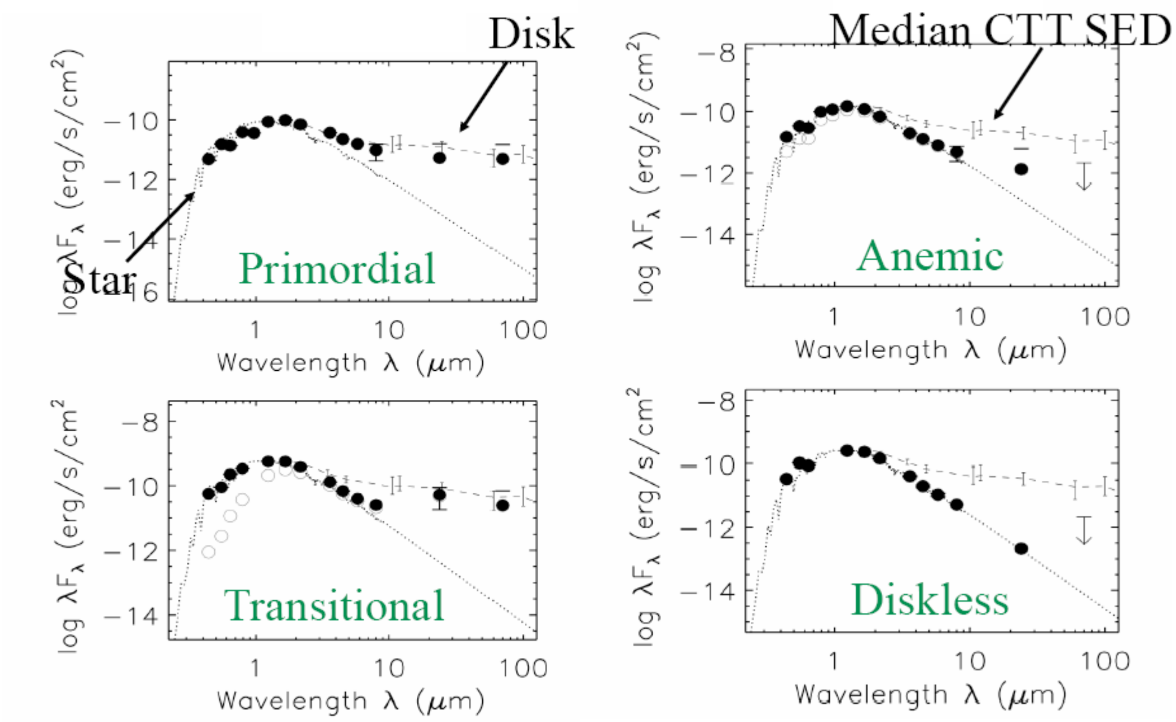
Debris disks
- rocks, dust, ice, gas-poor
- collisional grinding down of planetesimals

Anemic disks

fluxes at all λ < primordial disk

active or passive accretion

α-slope in between CTTSs and debris disk



Transitional

-near-IR flux < median of Tau & mid-IR fluxes ≥ median of Tau

-evolution of dust to larger sizes (i.e., anemic)

-combined effect of accretion and photoevaporation (i.e., cold)

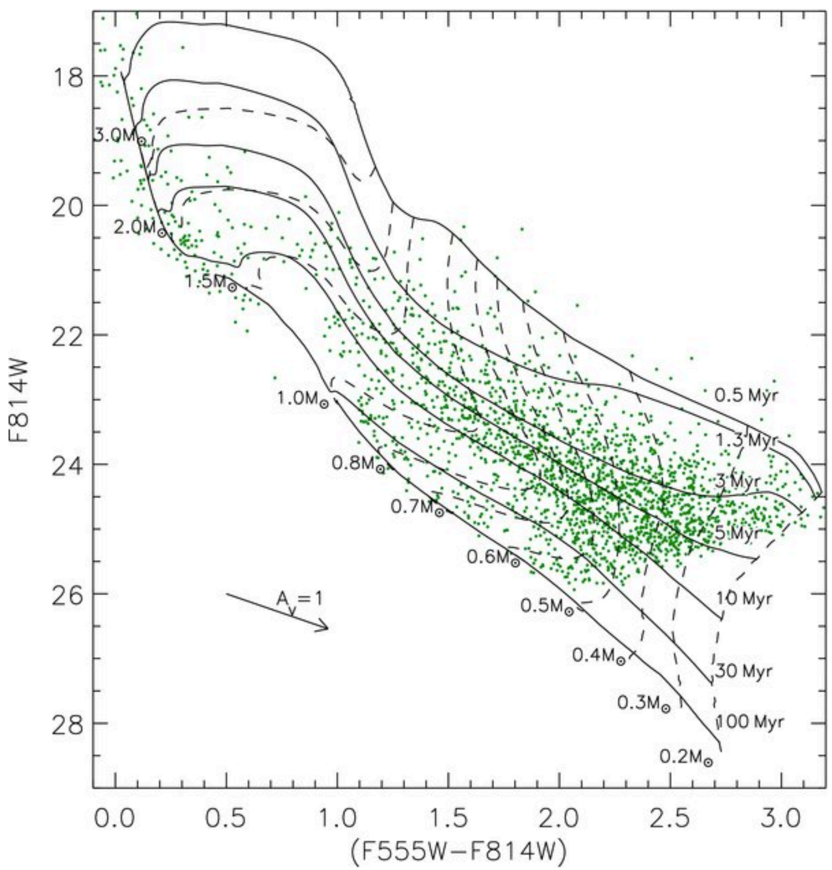
-dynamical effects of forming planets on structure, accretion rate and dust content of the inner disk (i.e., cold)

1) Grain growth and settling in disks
2) Photo-evaporation of disks by UV stellar flux
3) Disruption of disks by stellar companions/flybys
4) Planet formation

Evans et al. 2009, arXiv:0901.169 and ref. therein: The disktionary

Caveats on isochronal ages

LH95 (LMC), Da Rio et al. 2010



1) Photometric uncertainties, interstellar reddening effects, binarity, crowding, variability, accretion, etc. (e.g., Da Rio et al. 2010, ApJ 723, 166: age spread 2-4 Myr)

2) Age dispersion of a given stellar population depends on the size of the region. (Elmegreen 2000). The typical size of our region is 162"×162" (i.e. about 100 pc at the LMC distance) and an age dispersion up to a few to 10 Myr inside each region are to be expected.

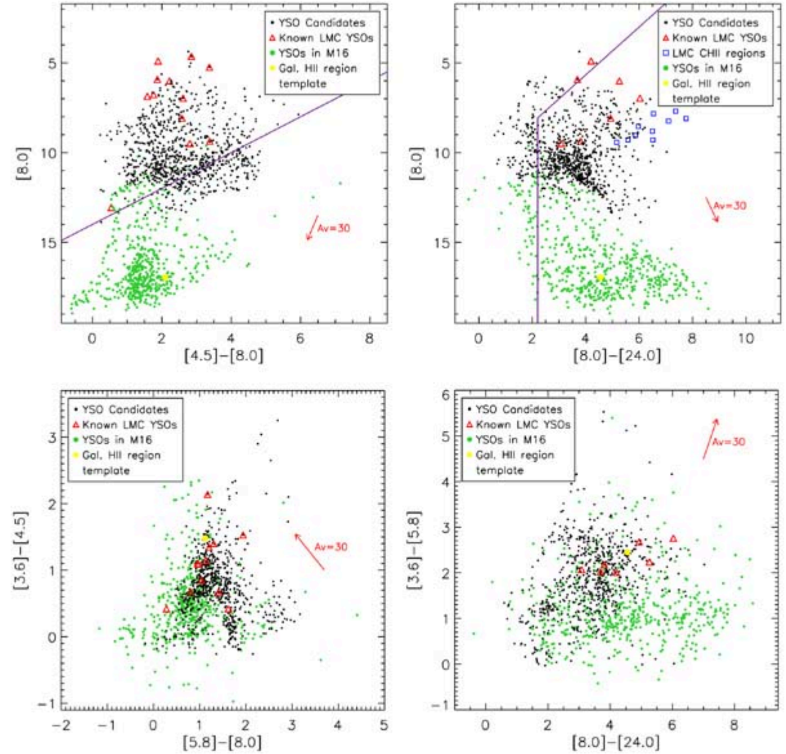
3) Baraffe et al. (2009): vigorous episodes of mass accretion at early stages of the stellar life (<1 Myr) can produce a luminosity spread in the HR diagram equivalent to a ~10 Myr age spread -> ages below a few Myr are highly uncertain and absolute ages are hard to determine, though relative ages are still reliable.

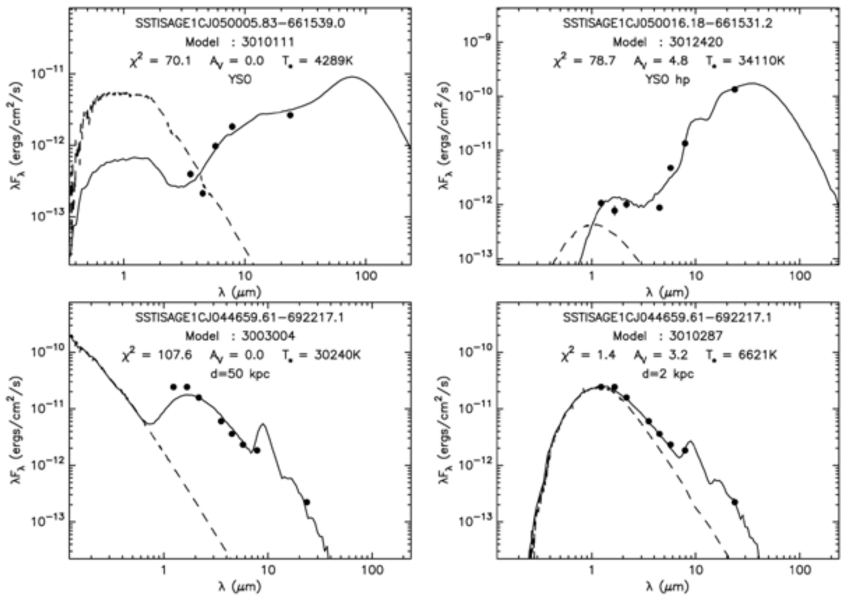
4) Most of the PMS stars in our sample are G-type (~80%) or late K-type stars (~20%). Hartmann (2003) discussed the uncertainties in the birth line of G-type stars (T_{eff}<5400 K), which results in a overestimate of their ages.

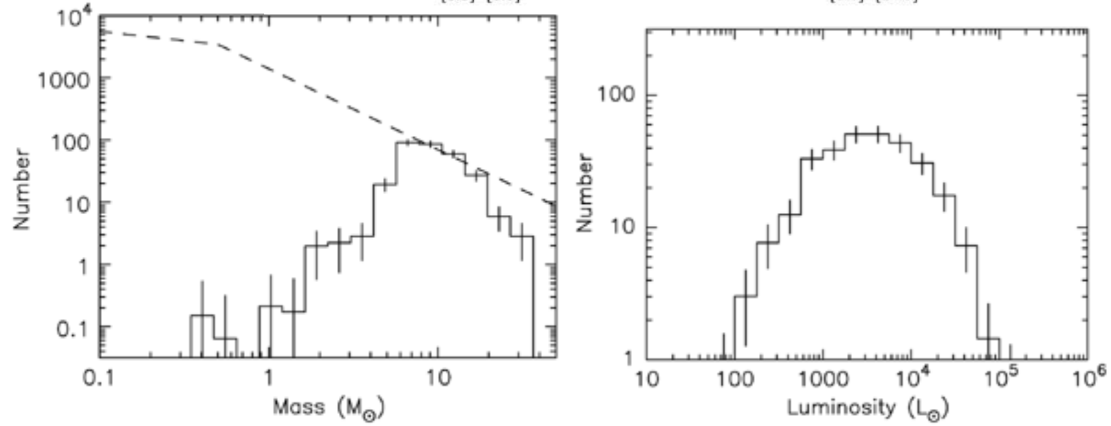
➢ ***Ages of statistical samples are, in principle, reliable and the global age differences between regions are real (see, e.g., Mayne et al. 2007).***

The Spitzer-SAGE survey of the LMC

- λ-range: 3.6-160μm (IRAC & MIPS)
- ~1000 YSO selected in regions of CMD free of other populations (evolved stars & galaxies)
- Contamination upper limit ~55%
- SED modeling of 299 high-probability YSOs
- Estimates of stellar mass, envelope infall rate, disk mass, and luminosity
- Candidates mass range: 0.3-30$M_{\odot}$ (complete 6-10$M_{\odot}$)
- About half of the sources are classified as Stage I still surrounded by infalling envelopes







Whitney et al. 2008, AJ 136, 18W