Herschel Spectroscopy of Massive Young Stellar Objects in the Magellanic Clouds

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Why study young stars in the Magellanic Clouds?

- ✦ nearby gas-rich galaxies: d ~ 50 kpc (LMC) d ~ 60 kpc (SMC)
  - ✦ detailed resolved studies
  - ✦ galaxies-wide view of star formation
- ✦ lower metallicity templates: $Z_{LMC} \sim 0.4\ Z_{\odot}$ and $Z_{SMC} \sim 0.2\ Z_{\odot}$
- ✦ variety of star formation environments from mini-starburst to low gas density
- ✦ Spitzer Space Telescope and Herschel Space Observatory facilitated large samples of massive YSOs
- ✦ Herschel spectroscopic survey of Magellanic YSOs

Magellanic YSOs selected for Herschel Spectroscopy

massive YSO properties:

- ✦ well studied with Spitzer
- ✦ range in luminosities
- ✦ “quiescent” environments
- ✦ range in properties (ices, maser sources, UCHII)

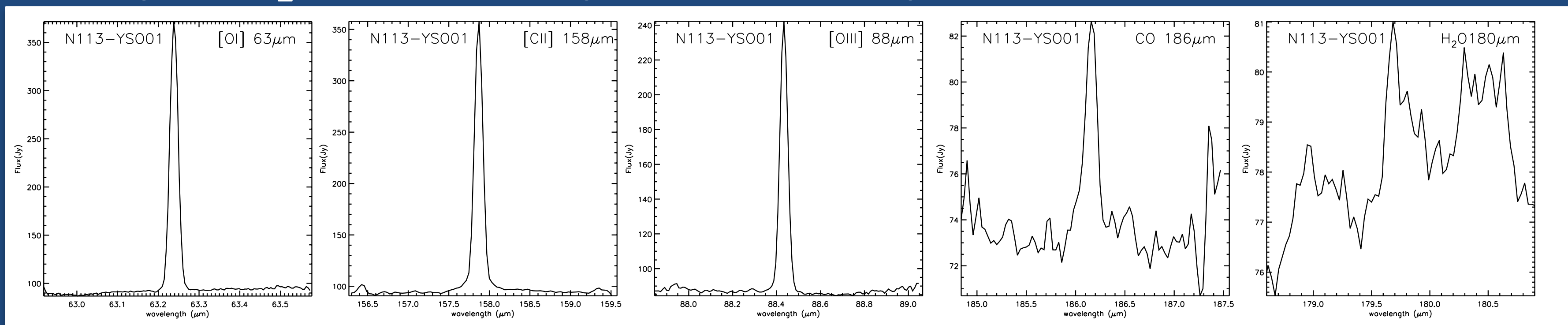
project goals:

- ✦ investigate emission line properties
- ✦ constrain cooling budget
- ✦ metallicity effects ?

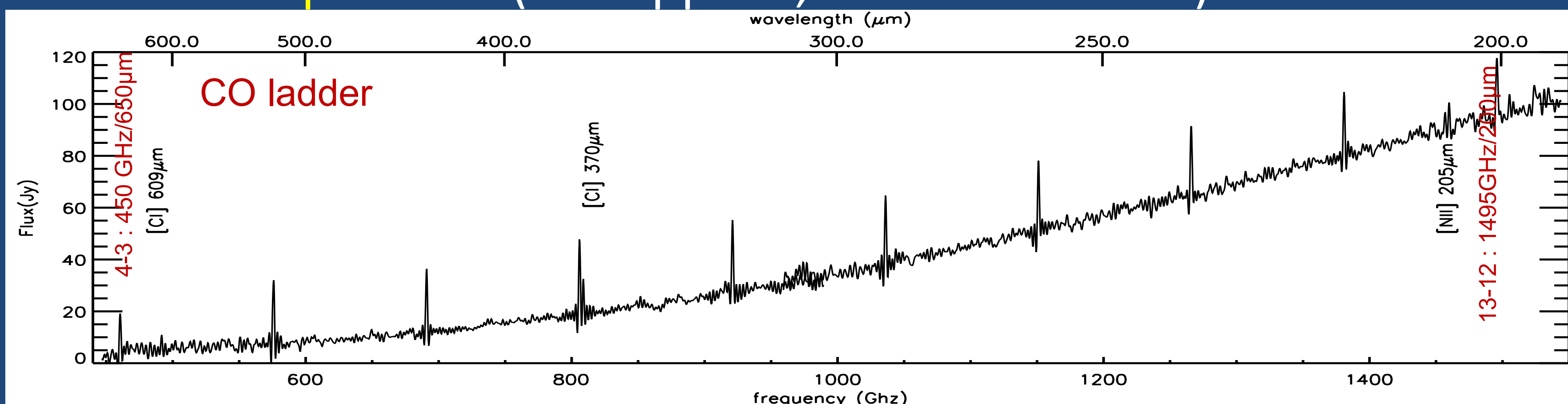
target	known properties	$M/M_\odot$	$L/10^3L_\odot$
LMC			
IRAS04514−6931	strong ice	25	68
IRAS05011−6815	maser	29	21
IRAS05328−6827	weak ice	17	13
LMC053705−694741	Herschel YSO	28	5
N113−YSO3	protocluster, UCHII, maser	33	246
N113−YSO4	protocluster, UCHII, possible maser	29	121
SAGE045400.9−691151.6	strong ice, maser	21	128
SAGE051024.1−701406.5	strong ice	16	18
SAGE051351.5−672721.9	weak ice	40	122
SAGE052202.7−674702.1	weak ice	15	28
SAGE052212.6−675832.4	weak ice	41	319
SAGE052350.0−675719.6	strong ice	17	57
SAGE053054.2−683428.3	strong ice	29	73
ST01	weak ice	21	41
N113−YSO1	maser	38	264
SMC			
IRAS00464−7322	strong ice	15	12
IRAS00430−7326	UCHII, strong ice, maser	26	71
N81−IRS1	protocluster, UCHII with outflow	16	54
S3MC00541−7319	strong ice	21	24
N88A	protocluster, UCHII, H_2 arc	28	195

Herschel spectroscopy of Magellanic YSOs

- PACS unchopped line scan: [OI] 63μm, [OIII] 88μm, [CII] 158μm, CO 186μm, H_2O 179.5/108μm, OH 79/84μm (beam~9.5-12")



- SPIRE FTS spectrum (SEC applied, beam ~16.5-42")



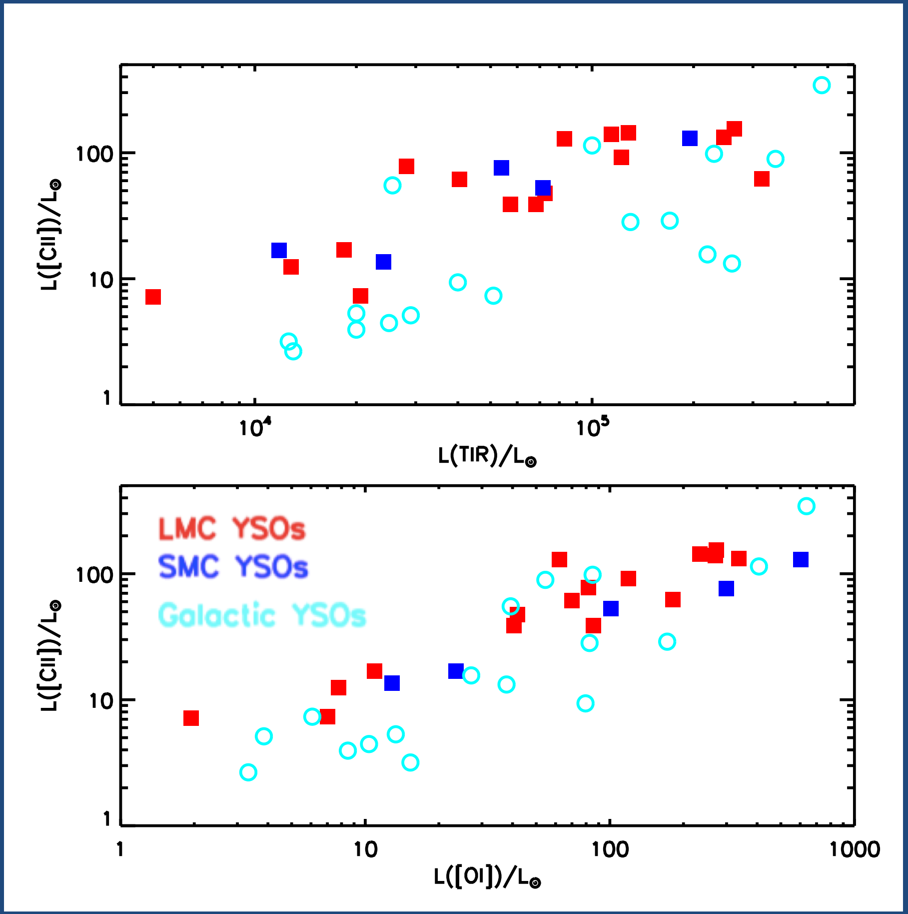
Detected atomic and molecular species

	PACS						SPIRE		
	[OI] 63μm	[CII] 158μm	[OIII] 88μm	CO 186μm	H_2O 179.5/108μm	OH 79/84μm	CO ladder	[CI] 370/609μm	[NII] 205μm
LMC	16/16	16/16	9/14	5/16	6/16	5/16	14/14	14/14	7/14
SMC	5/5	5/5	3/4	2/4	2/5	0/5	5/5	5/5	2/5

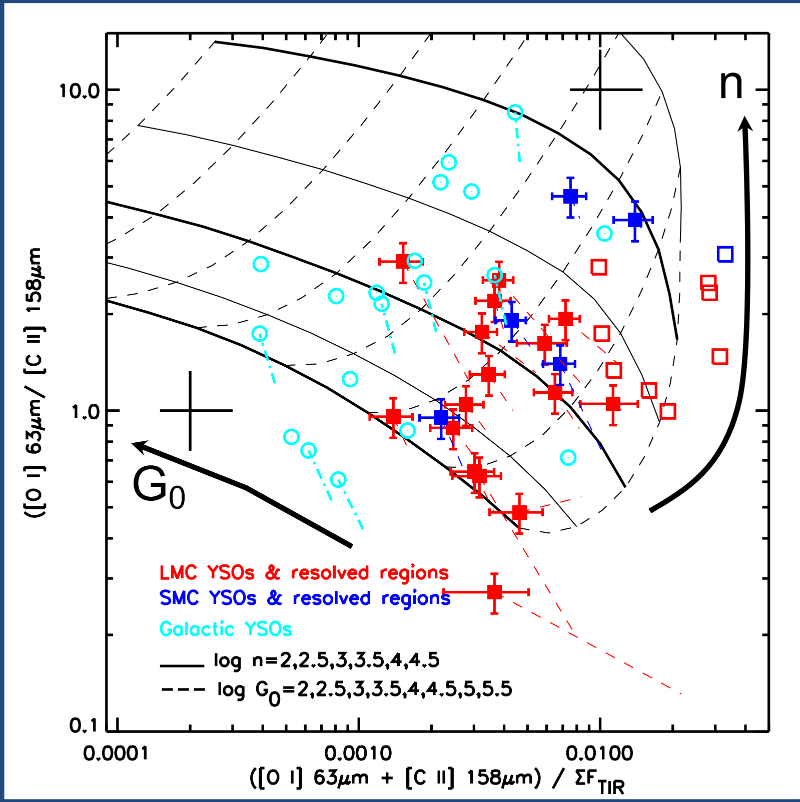
- [OI] and [CII] emission always observed
- CO ladder always detected; usable (SNR> 5) for 15 sources
- weak H_2O @179.5/108µm emission for 8 YSOs
- weak OH emission in 5 LMC sources; 2 LMC sources in absorption
- consistent with low H_2O and OH contribution to cooling for Galactic high-mass YSOs

Origin of atomic line emission

- ✦ [CII] & [OI] emission originates from PDRs and shocks; [CII] also from HII regions and diffuse neutral and ionised gas
- ✦ common origin for [OI], [CII] line emission in PDRs
- ✦ Galactic YSO sample observed with ISO LWS (d ~ 1-10 kpc)
- ✦ line emission enhanced wrt dust continuum in Magellanic Clouds (e.g. Israel & Maloney 2011)



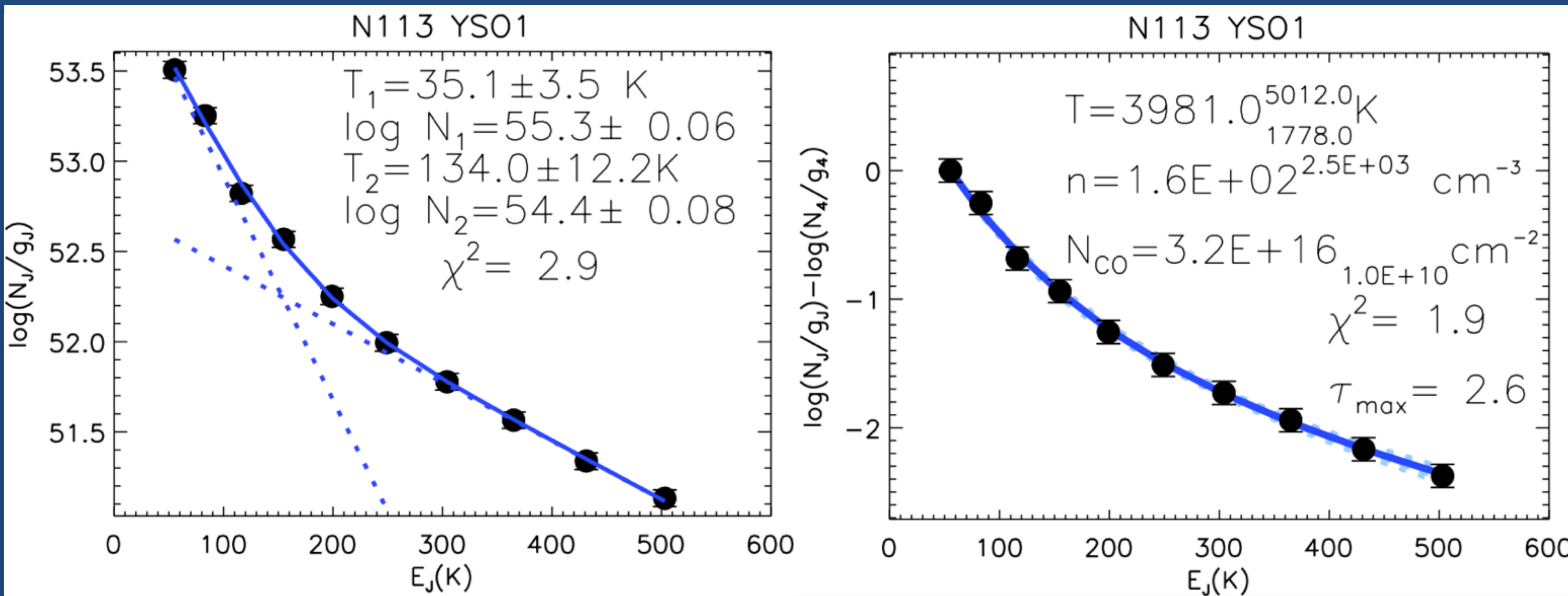
Photoelectric efficiency & ISM properties



PDR Toolbox (Pound & Wolfire 2008; Kaufman 2006)

- MCs YSOs: higher photoelectric efficiency
- SMC PAHs emission from neutral small grains (Sandstrom et al. 2012; Oliveira et al. 2013)
- low G_0/n consistent with low metallicity dwarf galaxies (Cormier et al. 2015)
- larger UV photon mean free path leads to larger distance to PDR face
- UV field dilution and reduced grain charging
- distinct ISM properties and structure at low metallicity (porous and clumpy ISM Madden et al. 2006; Cormier et al. 2015)

SPIRE CO rotational diagrams

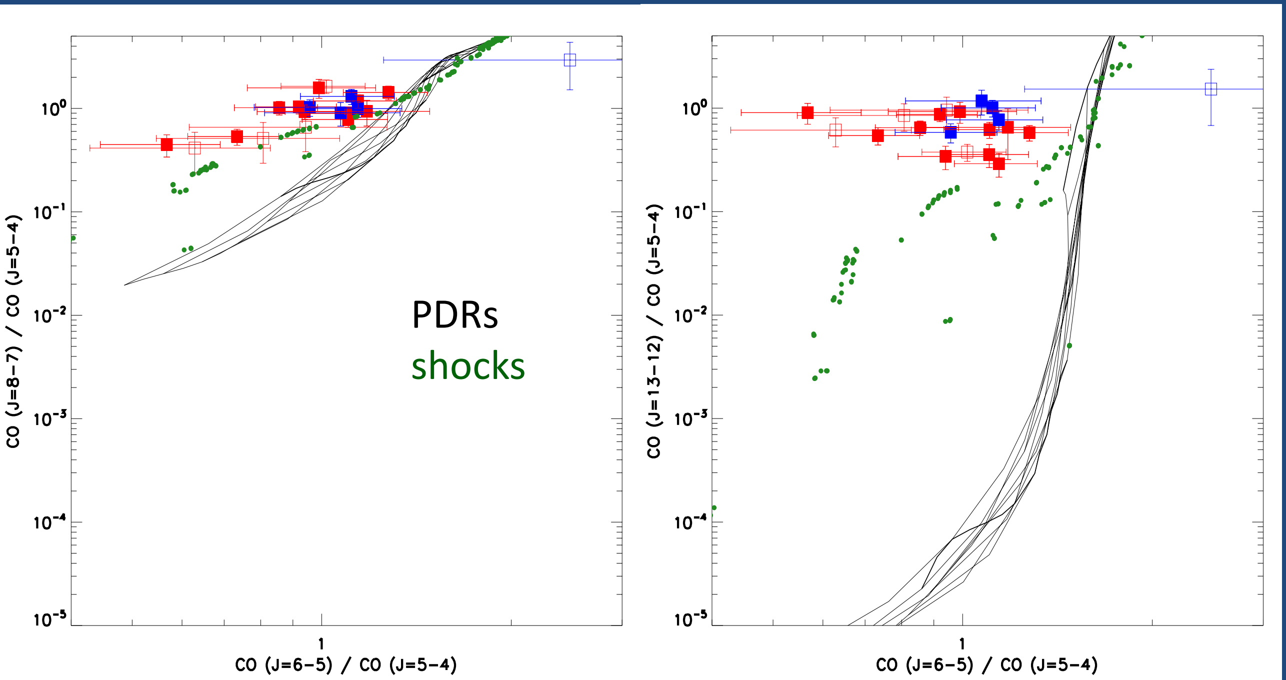


- ✦ optically thin LTE gas
- ✦ T_1 ~ 35 K, T_2 ~ 132 K (slopes), N ~ 10^{55} mol. (ordinate)
- ✦ also continuous T distribution

- ✦ non-LTE gas models (Neufeld 2012)
- ✦ single uniform density & temperature gas
- ✦ T $\gtrsim$ 1000 K, n $\lesssim$ 10^4 cm^{-2}
- ✦ gas clearly subthermal

Origin of CO emission

- PDR versus shocked gas



- PDR Toolbox (log(n, G_0) = 2-6)
- Paris-Durham shock models (Lee et al. 2016; Flower & Pineau des Forêst 2015): log n_{ps}=3-6, b=1, v= 4-20 kms^{-1} solar metallicity
- better agreement with shocks
- L(CO)/L(TIR)>0.01% supports shocks
- hint of multiple components

shock origin for CO emission

Properties of CO emission

- what we know from Galactic and Magellanic YSOs
  - SLEDs fitted by either multiple-components of thermalised cold/warm gas or subthermal hot gas (e.g. Manoj et al. 2013)
  - reasonably consistent properties (e.g. gas temperature) across YSO properties (i.e. weak dependence on YSO luminosity)
  - emission originates from shocked gas
  - over J ∈[4:44] multiple spatially distinct components: T~30-50, 100, 300, 700 K (e.g. Yang et al. 2018)
  - kinematic evidence from H_2O and CO Herschel-HIFI observation Kristensen et al. 2017 and references therein

Properties of CO emission

- what w
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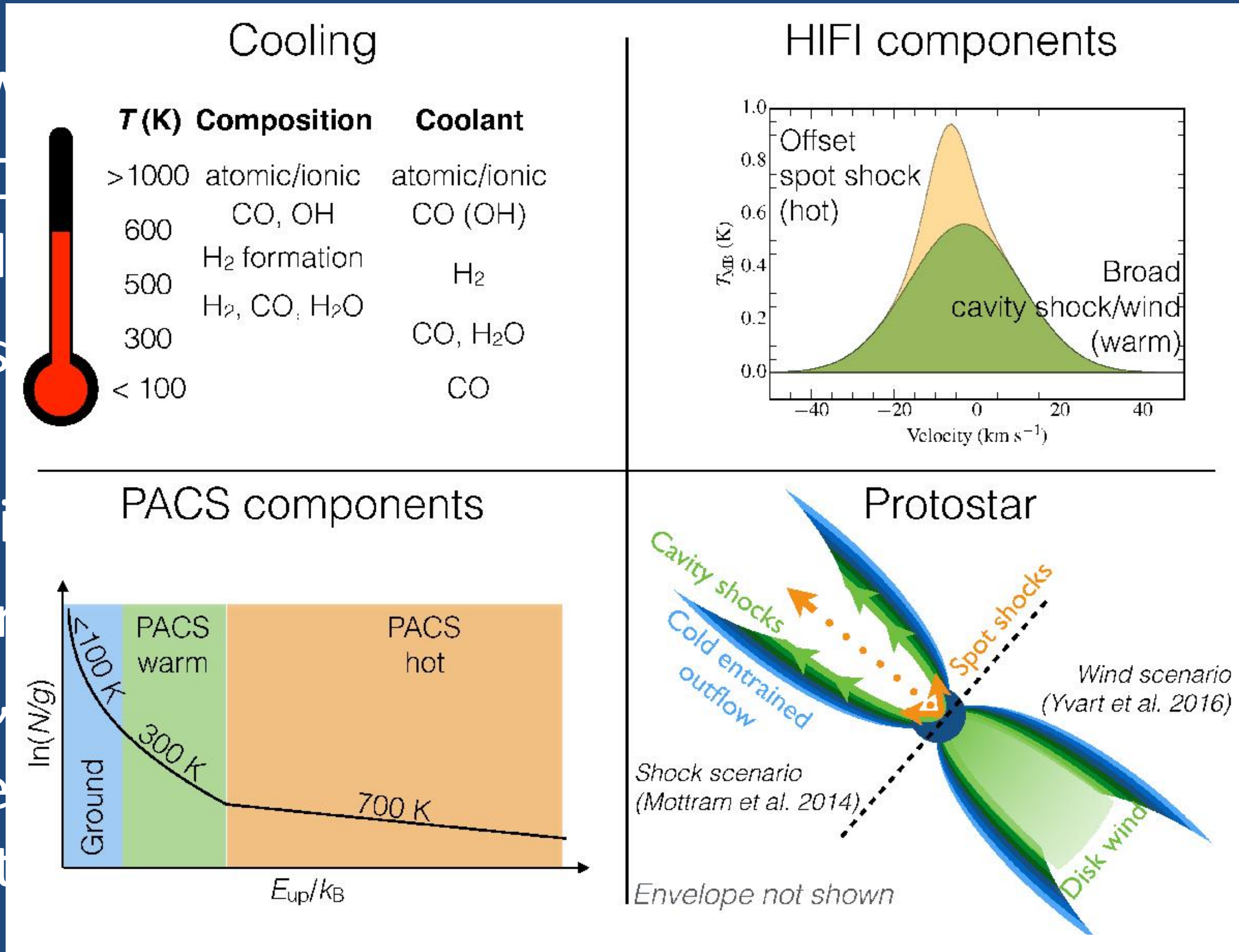
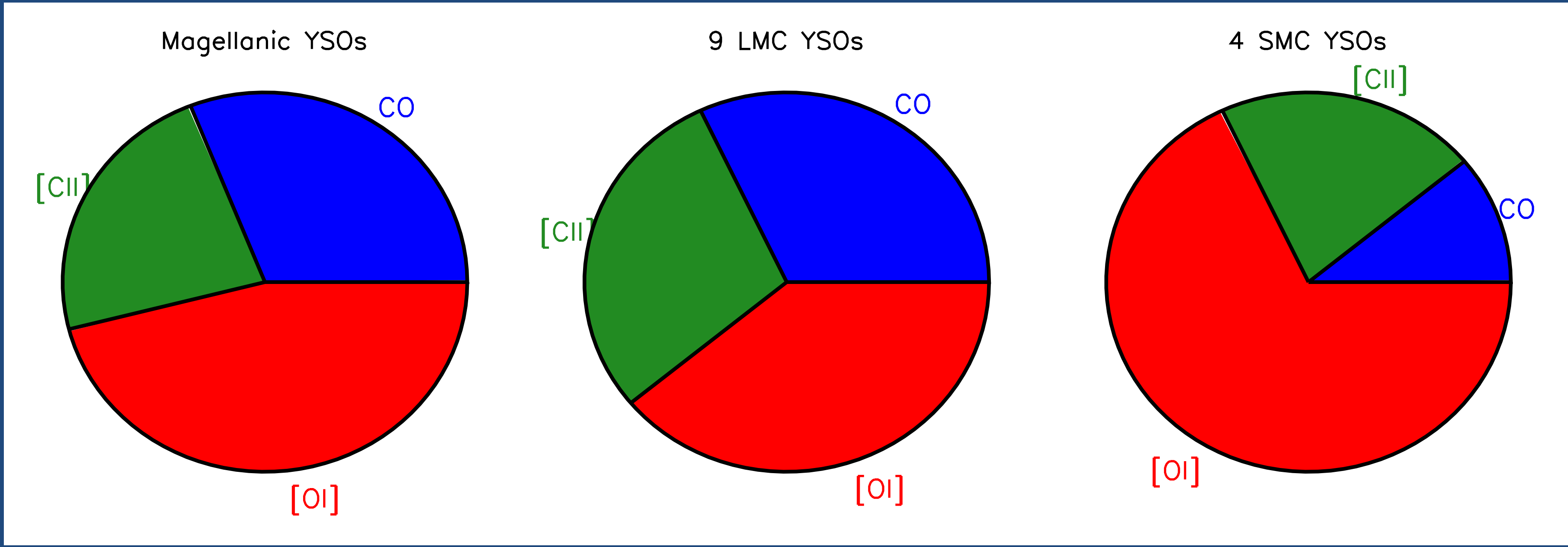


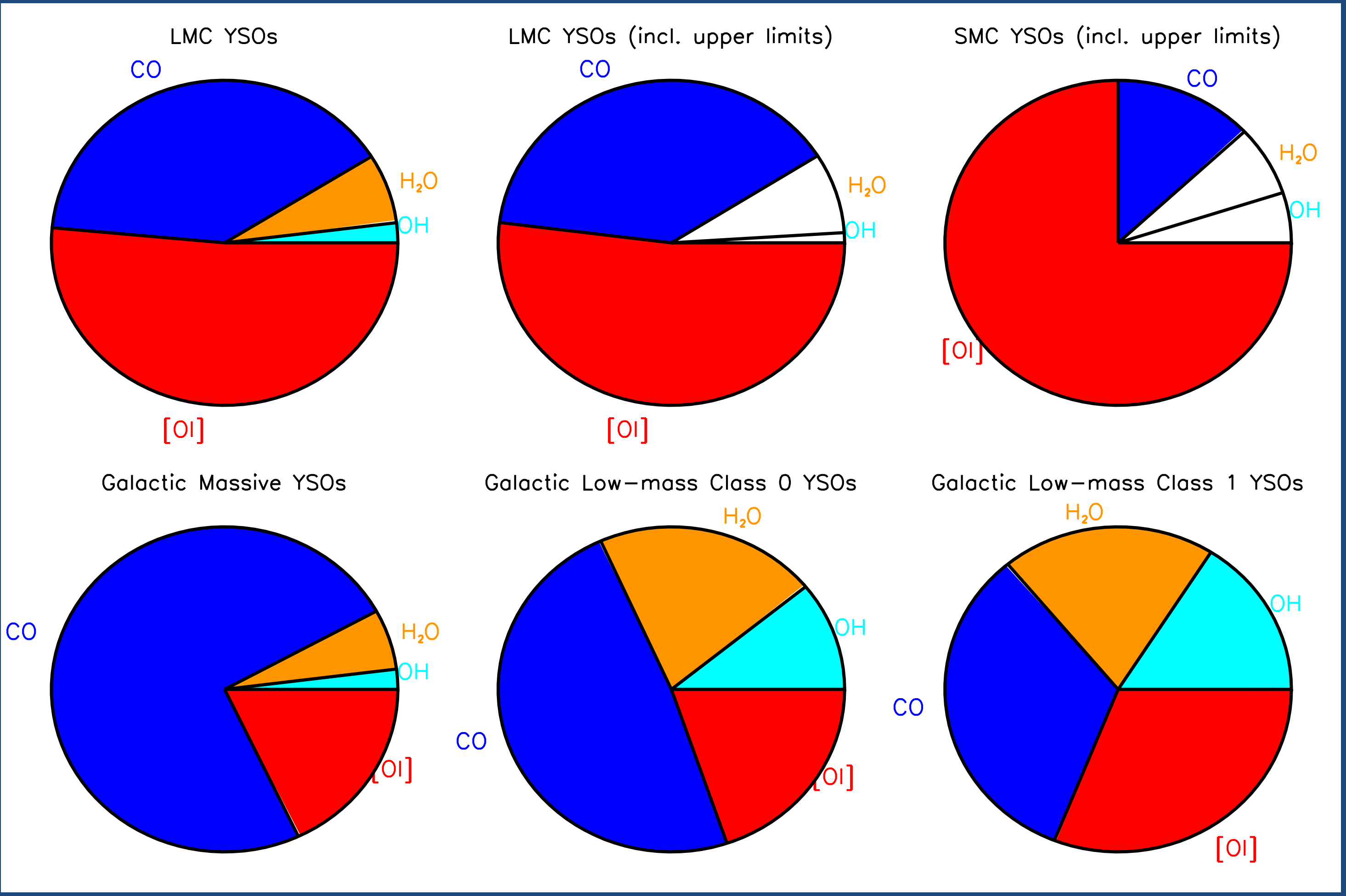
e.g. Kristensen et al. (2017)

Main cooling species



- median contributions (with large spread)
- [OI] main coolant for 10/13 YSOs, followed by CO and [CII]
- SMC YSOs: marked decrease in CO contribution (3/4 sources)
- linked to reduced gas-phase CO abundance (e.g. Leroy et al. 2007)

Cooling budgets for Galactic & Magellanic YSOs



Galactic samples: Karska et al. (2013, 2014, 2018)

For Galactic YSOs:

- ✦ CO dominates cooling
- ✦ shift to [OI] as YSO evolves; CO dissociated
- ✦ H_2O and OH important only for low-mass YSOs; easily photodissociated

For Magellanic YSOs:

- ✦ [OI] dominates cooling
- ✦ CO cooling further reduced for LMC
- ✦ small contribution from H_2O and OH
- ✦ known YSO properties

Summary

- ✦ [OI] and [CII] emission indicate higher photoelectric efficiency in MC YSOs, consistent with reduced grain charge and increased UV dilution
- ✦ SPIRE CO rotational diagrams consistent with Galactic observations (cooler components) and shock origin
- ✦ weak H_2O and OH emission consistent with modest role in massive YSO cooling
- ✦ [OI] dominates cooling in MC YSOs; CO cooling possibly further reduced in SMC YSOs
- ✦ different cooling budgets between Galactic and MC YSOs