The Youngest Protostars in the Large Magellanic Cloud

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Spitzer Studies of the YSOs in the Large Magellanic Cloud

– inventory of the YSOs throughout the entire LMC:

Whitney et al. (2008/SAGE; "Surveying the Agents of Galaxy Evolution"; PI M. Meixner)

Gruendl & Chu (2009)

Identified ~1800 intermediate to high-mass YSOs in the LMC

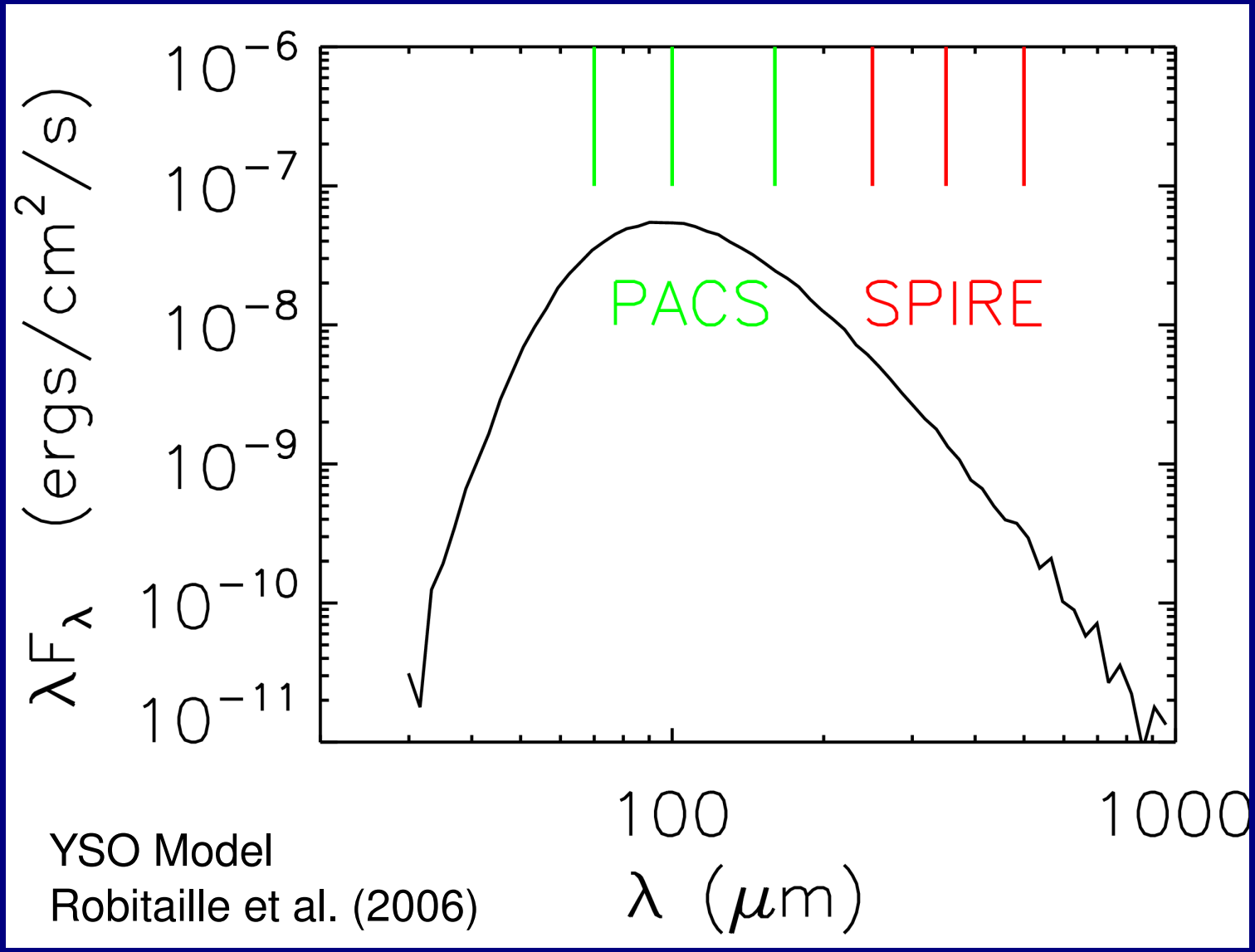
– individual star formation regions: identification of the YSOs; triggered star formation on a local scale

N 63 and **N 180 (**Caulet et al. 2008)
N 44 (Chen et al. 2009)
N 159 (Chen et al., 2010)
N 206 (Romita et al., 2010)

– spectroscopic confirmation of nature of the YSO candidates; ice chemistry (Shimonishi et al. 2008; Seale et al. 2009; Oliveira et al. 2009/SAGE-Spec; van Loon et al. 2009/SAGE-Spec)

~300 spectroscopically confirmed YSOs

Spitzer studies missed massive Stage 0 protostars



age ~ 10^4 years

$M_* \sim 16\ M_{sun}$

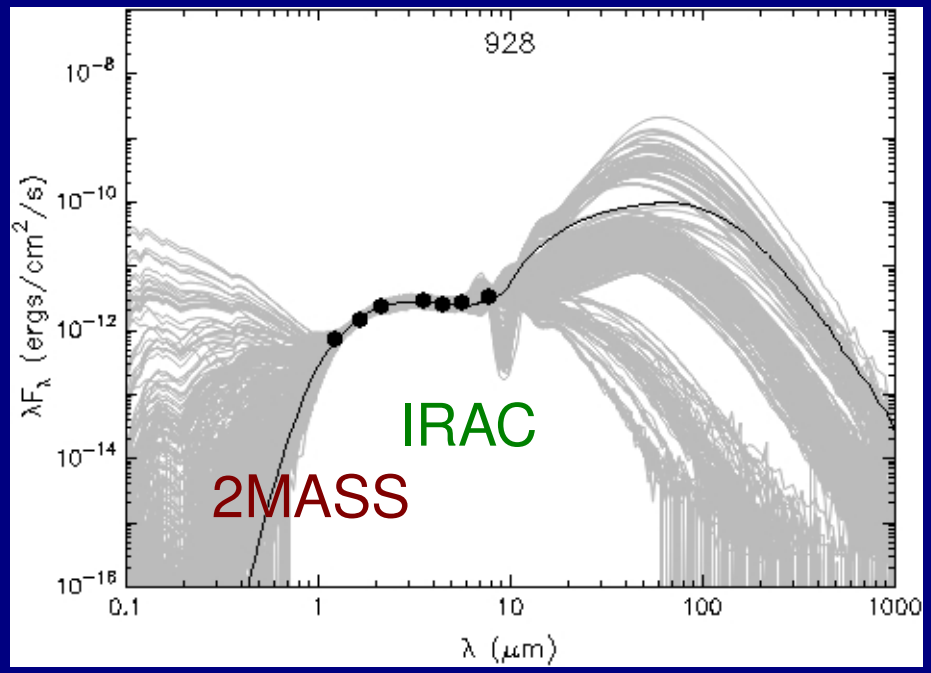
$\dot{M}_{env} \sim 5 \times 10^{-3}\ M_{sun}$ / yr

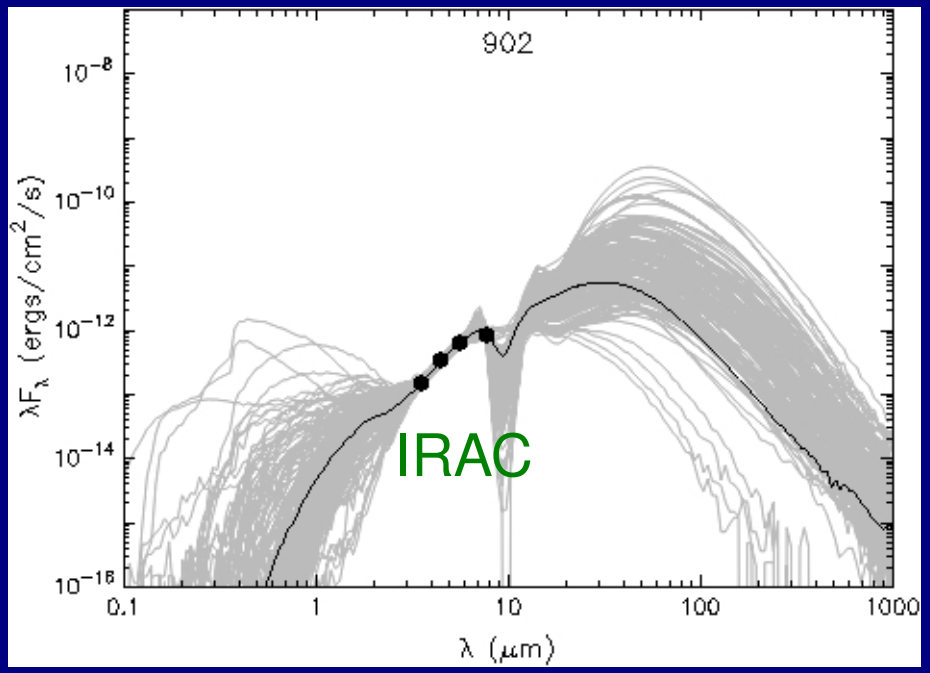
$L_{tot} \sim 7 \times 10^3\ L_{sun}$

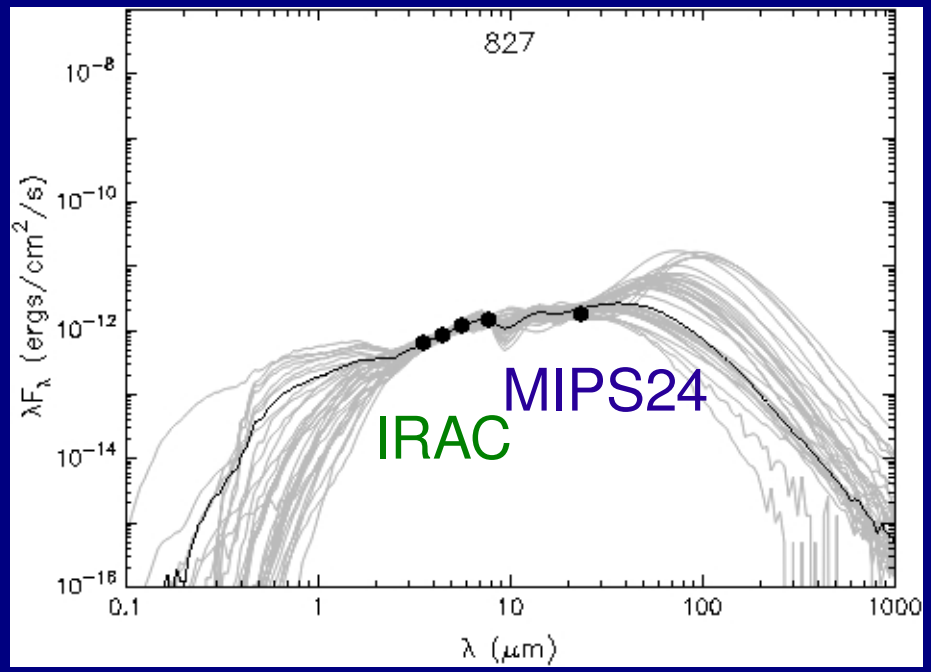
$M_{env} \sim 9 \times 10^2\ M_{sun}$

massive cold dust clouds/envelopes/mantles

YSO SEDs: importance of longer wavelengths





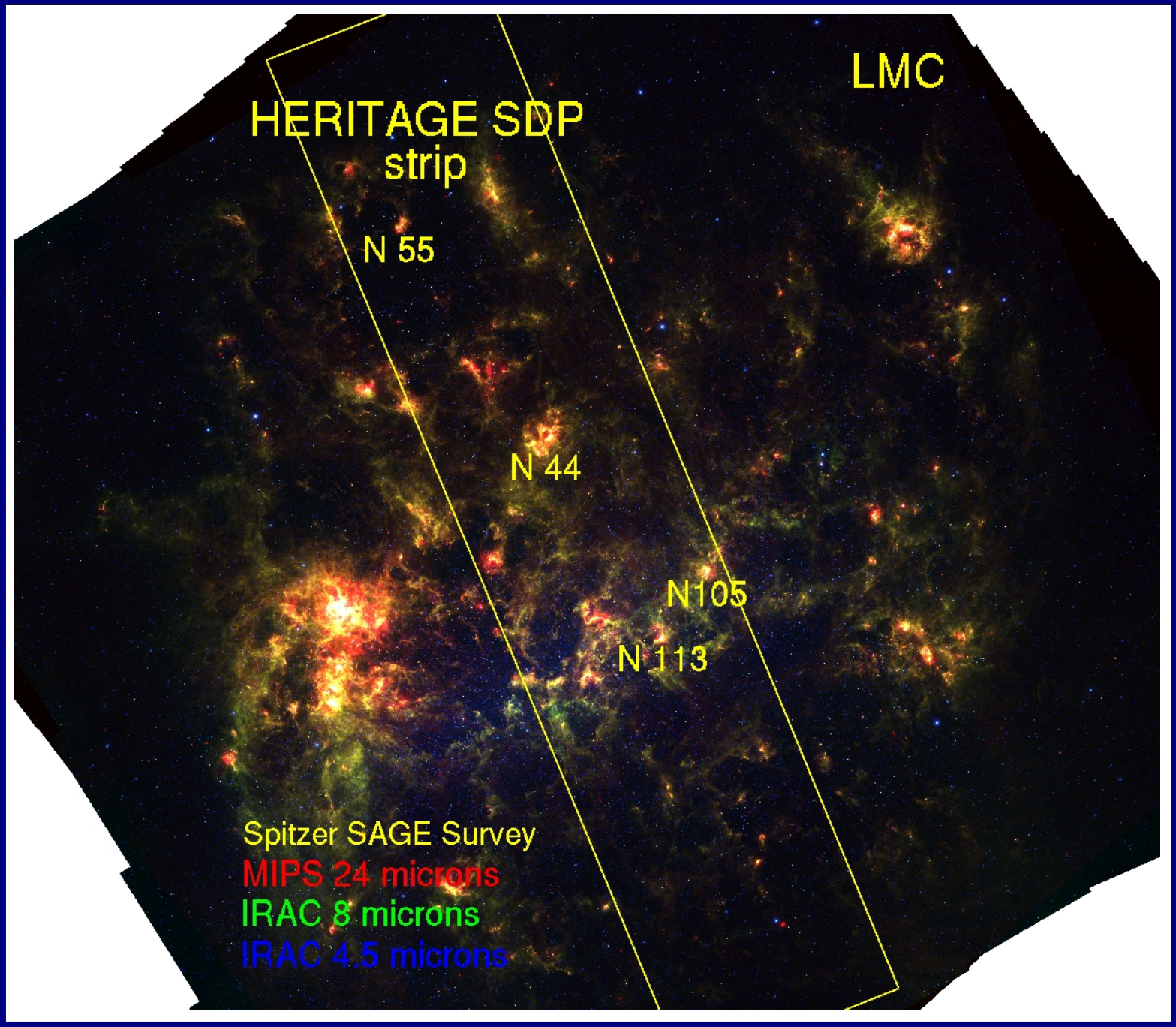


λF_λ

$\lambda(\mu m)$

constrain YSO models → better physical parameters and evolutionary stages

HERITAGE Science Demonstration Program



PI: M. Meixner (STScI)

– one slice through the center of the LMC

– two 9h AORs

– PACS & SPIRE parallel

PACS:
100, 160 μm

SPIRE
250, 350, and 500 μm

HERschel Inventory of The Agents of Galaxy Evolution (HERITAGE) in the Magellanic Clouds
→ 238 hour Open Time Key Program

Source Selection

- We selected ~640 sources by hand from *Herschel*/HERITAGE images
- aperture photometry

- Removed:
  * sources that could not be unambiguously identified due to multiplicity or complex diffuse emission
  * ~250 sources affected by striping in PACS bands
  * several sources that are likely to be background galaxies, AGNs, or evolved stars

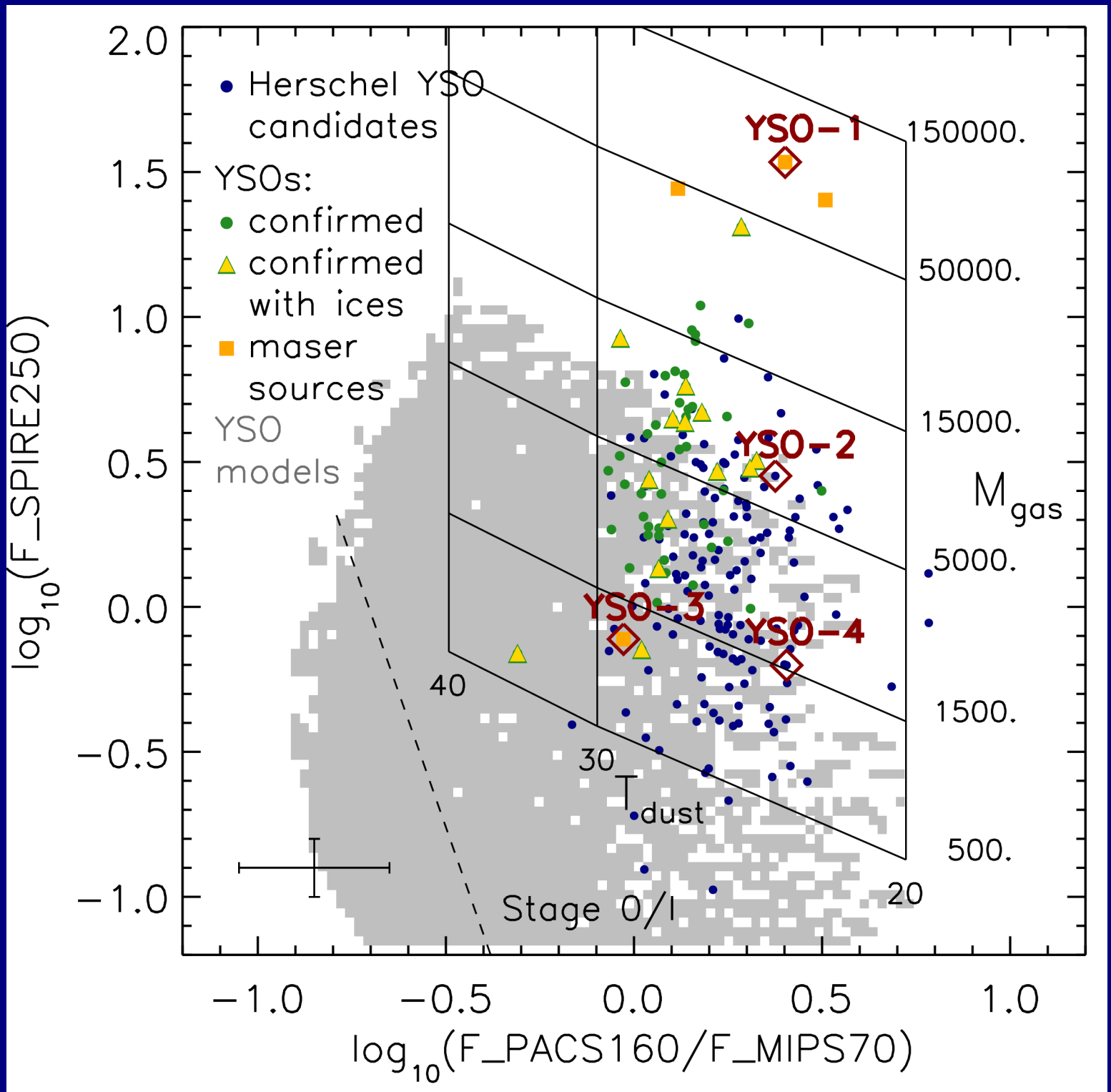
- Required:
  * reliable photometry spanning at least ~6-100 μm
  * environment consistent with young age
  * SEDs typical for the YSOs (YSO model SEDs as a guide)

Final list: 207 YSO candidates; 40% new

Goals

- Assess how *Herschel* changes our understanding of star formation based on the detailed analysis of 4 embedded YSOs.

- A complete analysis will be performed when the complete and higher quality HERITAGE survey data is available.



Far-IR CMD

YSO models from Robitaille et al. (2006)

grid – optically thin greybody emission

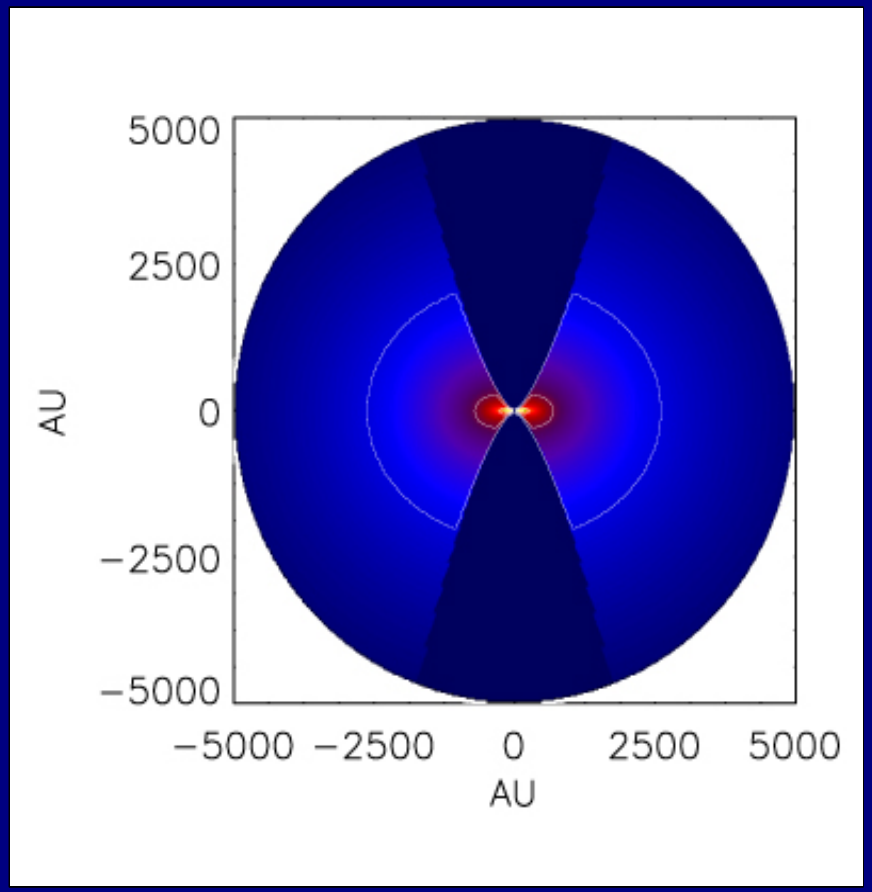
Herschel YSO candidates:

- Stage 0/I

- have very cool and massive circumstellar envelopes

YSO MODELS
Robitaille et al. (2006, R06)

the large grid of 2D radiation transfer models



Geometry:
Stellar source that illuminates a dusty disk
Envelope with bipolar cavities

20,000 YSO models at 10 viewing angles each
14 physical parameters

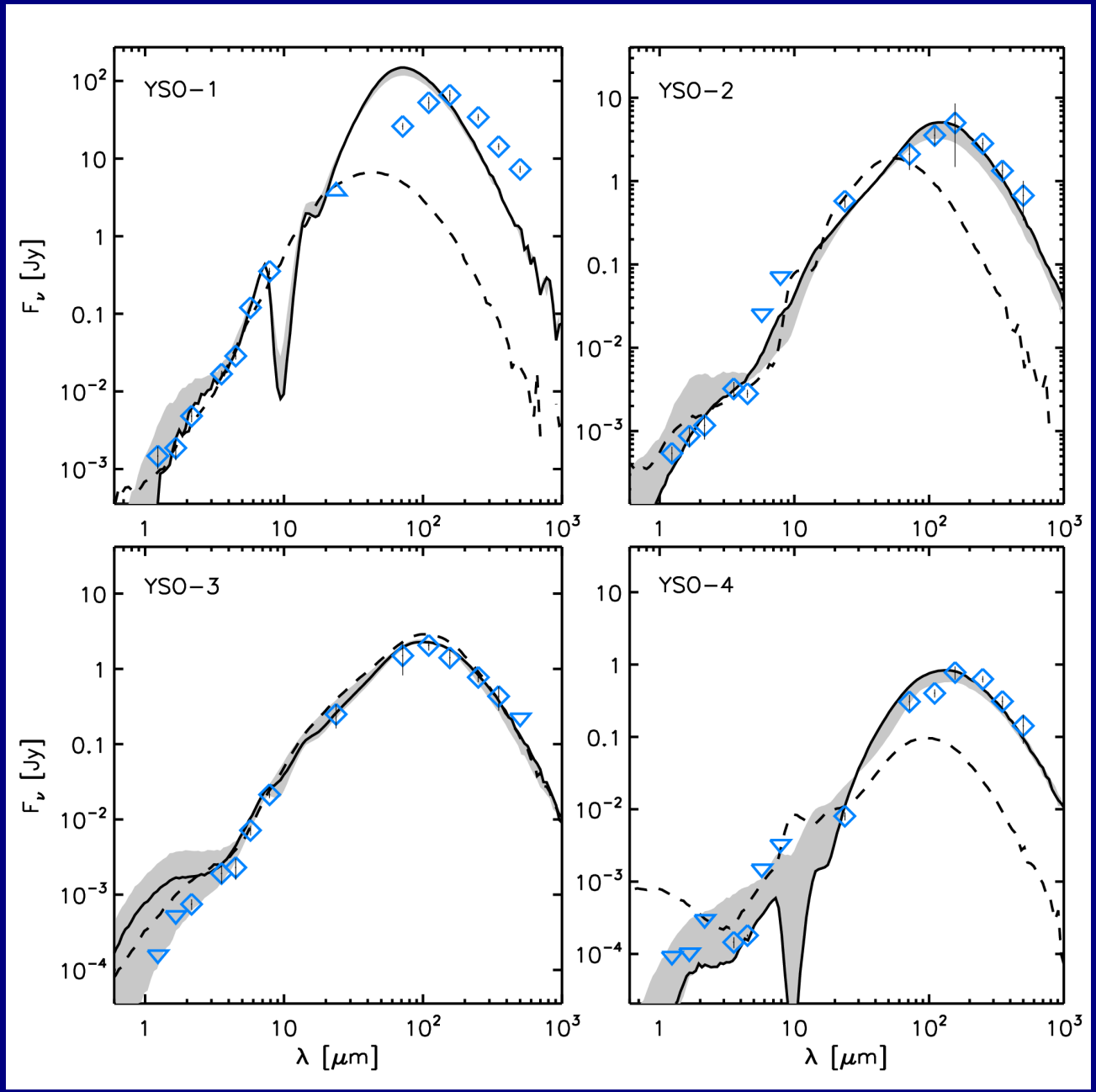
YSO Evolutionary Stages:

Stage 0/I $\dot{M}_{env} / M_* > 10^{-6}$ yr^{-1}

Stage II $\dot{M}_{env} / M_* < 10^{-6}$ yr^{-1} and $M_{disk} / M_* > 10^{-6}$

Stage III $\dot{M}_{env} / M_* < 10^{-6}$ yr^{-1} and $M_{disk} / M_* < 10^{-6}$

SED Fitting with Current YSO Models:
analysis for 4 typical embedded YSOs



grey:
the range of well-fitting models from the R06 YSO grid ($\lambda < 500$ μm)

black line:
the single best-fitting R06 model ($\lambda < 500$ μm)

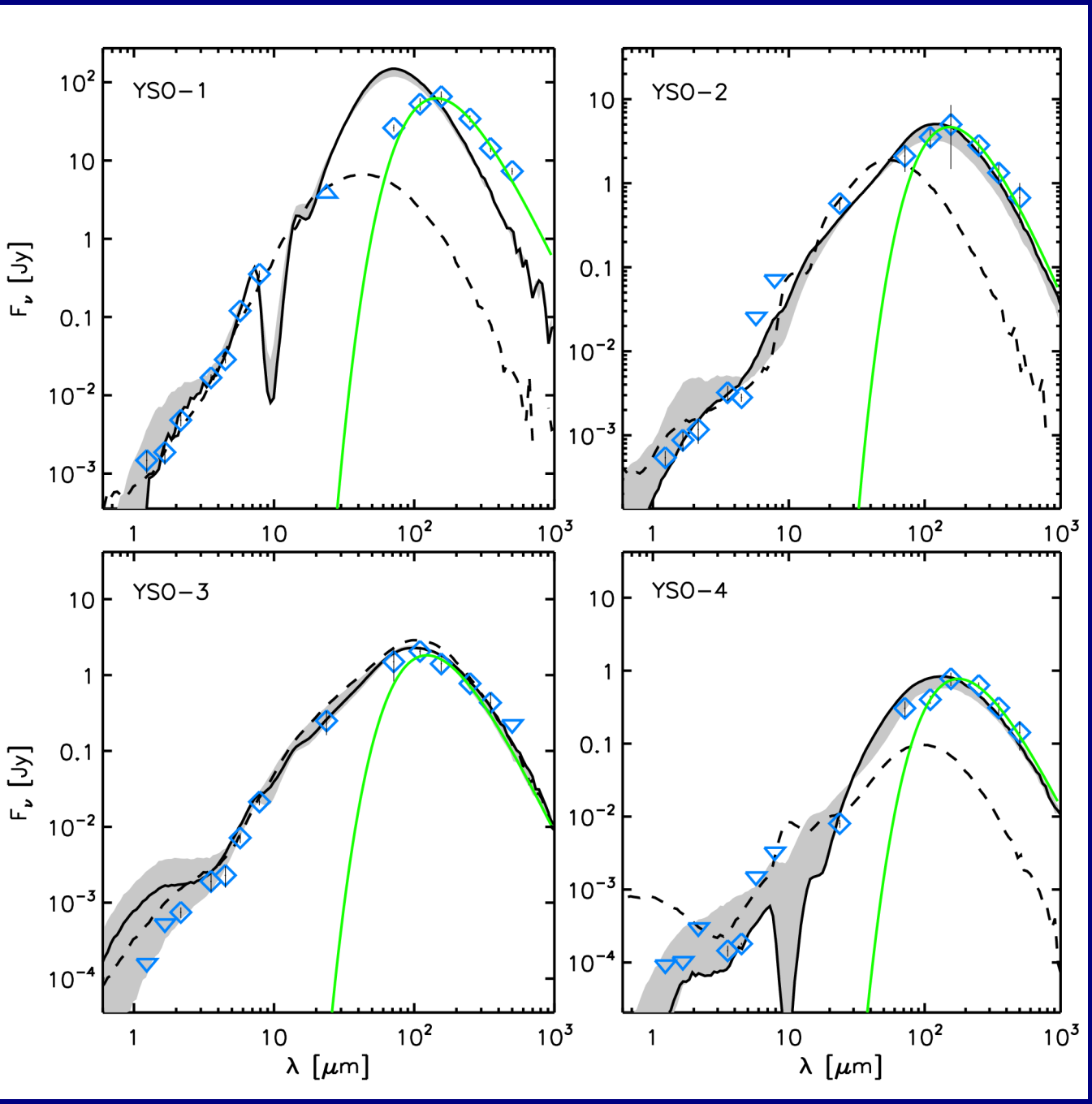
dashed black line:
the best-fitting model without *Herschel* data ($\lambda < 50$ μm)

Fits **with** *Herschel* data:

much better constraint on SED fits
→ reduced range of best-fit models
→ reducted uncertainties of physical parameters

$\dot{M}_{env}$ /M_* increases from ~10^{-5} to ~10^{-4} M_{sun} yr^{-1}
→ ages < 104 yr
→ *Herschel* traces the youngest YSOs

Greybody Fitting



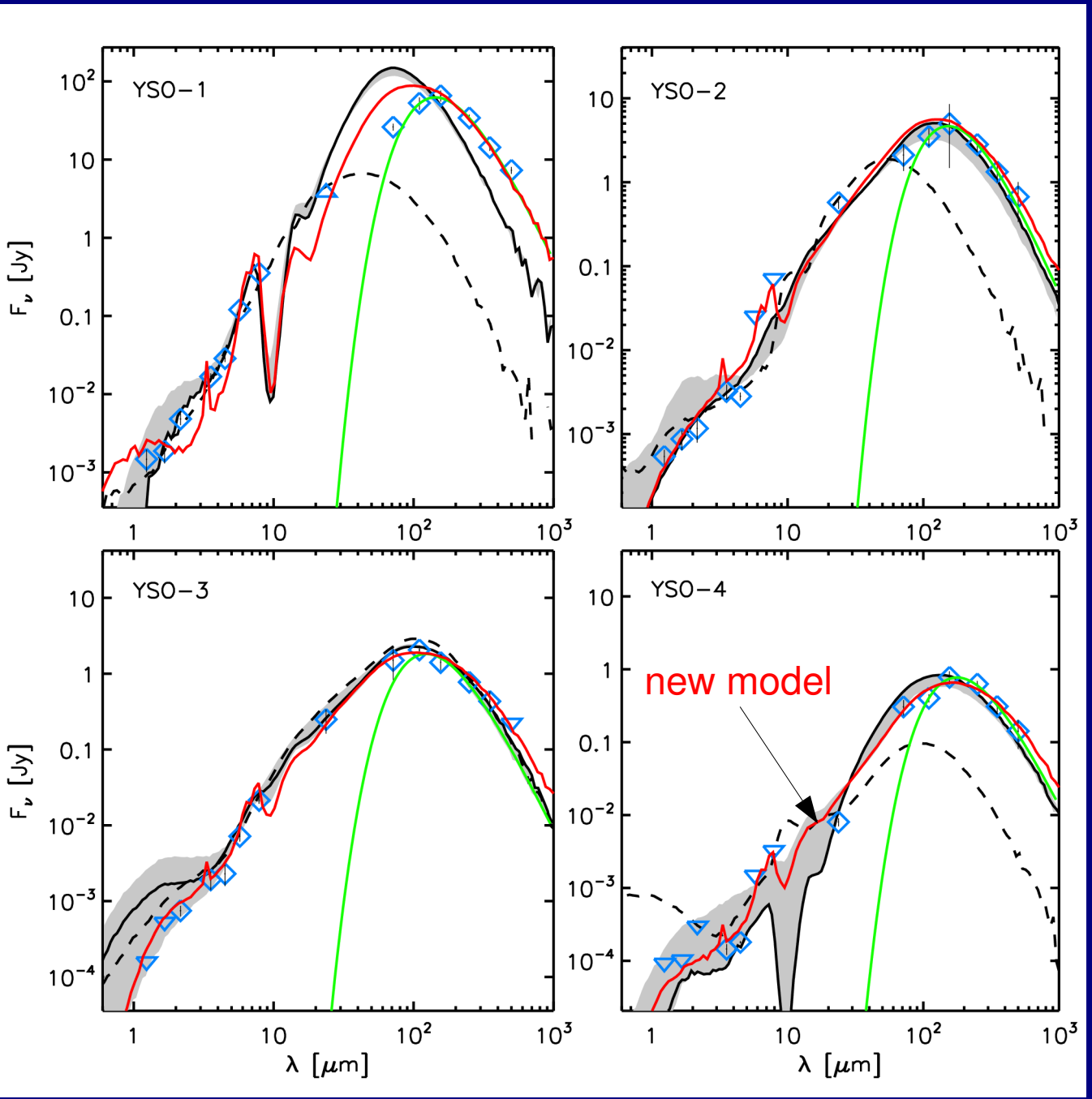
green line:
single-temperature greybody ($\lambda > 100$ μm)

$L_{far\text{-}IR}$ / L_{bol} ~ circumstellar to total mass ratio

$L_{far\text{-}IR}$ / L_{bol} ~ 0.2 – 0.5
→ consistent with Class 0 definition

T_{dust} ~ 16 - 24 K
→ consistent with far-IR colors and young age

New Dust Radiative Transfer Models



Present R06 models designed for *Spitzer* data:
$R_{out} \leq 0.5$ pc, $T \geq 30$ K

→ do not include envelope of cooler dust and gas further from the source

→ **new models** require more cold CSM

– larger envelope radii

– heating by external radiation

– PAH emission

Critical evolutionary parameters do not change significantly from the R06 best fits.

– multiplicity in future models

Conclusions

Herschel can offer us, for the first time, an inventory of the earliest stages of protostellar formation throughout an entire galaxy!

– *Herschel* is very effective in identifying cold YSOs in the LMC.

– Adding *Herschel* data to existing *Spitzer* and near-IR observations results in significantly improved analysis of YSOs:

- Nearly all sources detected by *Herschel* are Stage 0/I, very young, with a high ratio of circumstellar to stellar mass.
- *Spitzer* observed preferentially the warmest inner parts of YSO CSM - it takes *Herschel* to see the full CSM including massive cold outer regions
- *Herschel* photometry significantly constrains model SED fits
- *Herschel* data force further model development because they require more cold CSM than the best present models provide