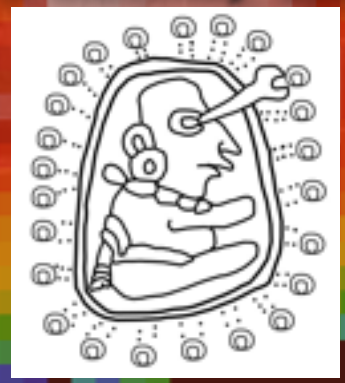
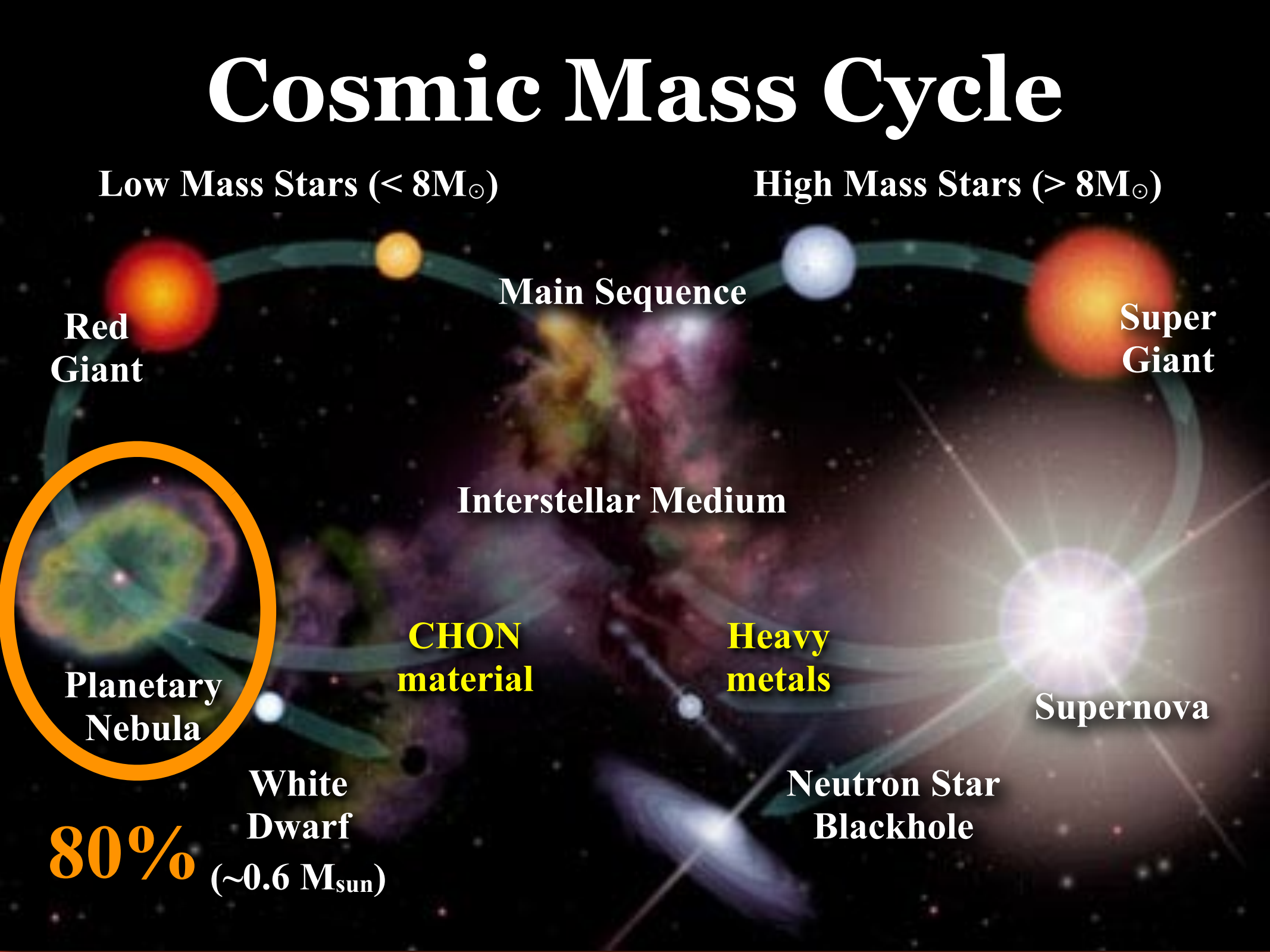
Hershel Planetary Nebula Survey (HerPlaNS)

Toshiya Ueta
Associate Professor, University of Denver, USA
JSPS Invitation Fellow, ISAS/JAXA, Japan

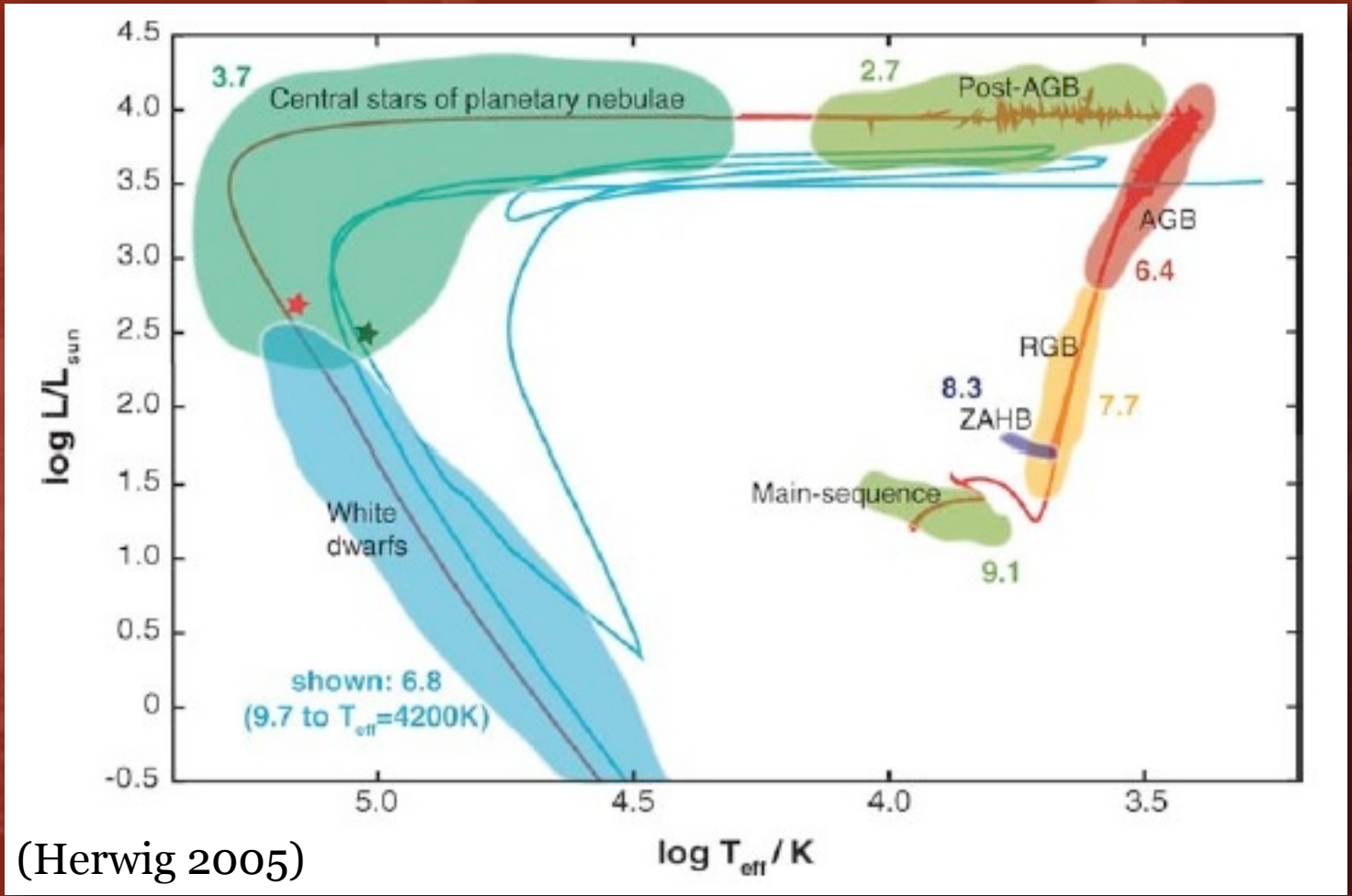


APN VI, Riviera Maya, Nov 6 2013

Cosmic Mass Cycle



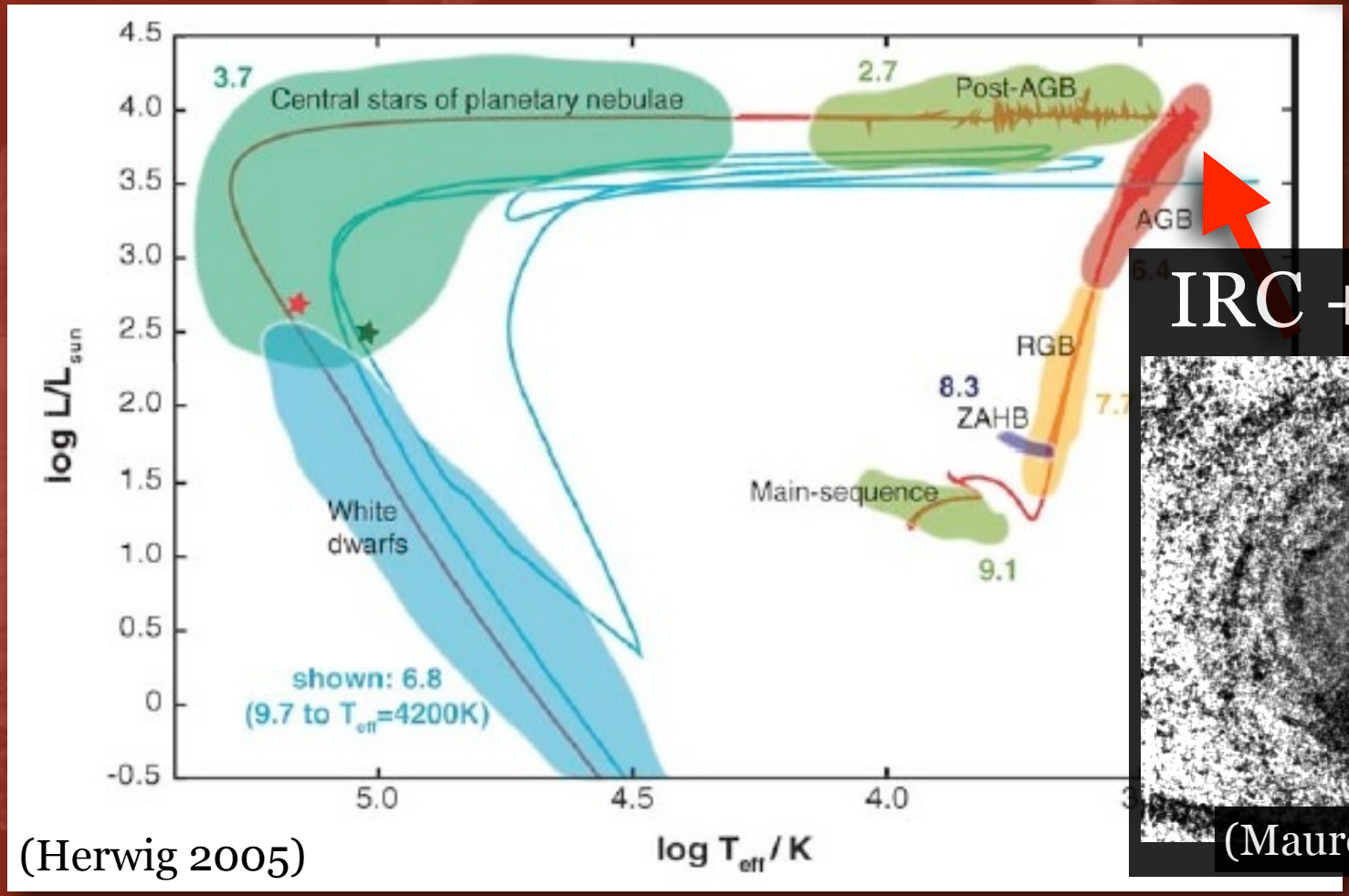
Shell Morphologies



(Herwig 2005)

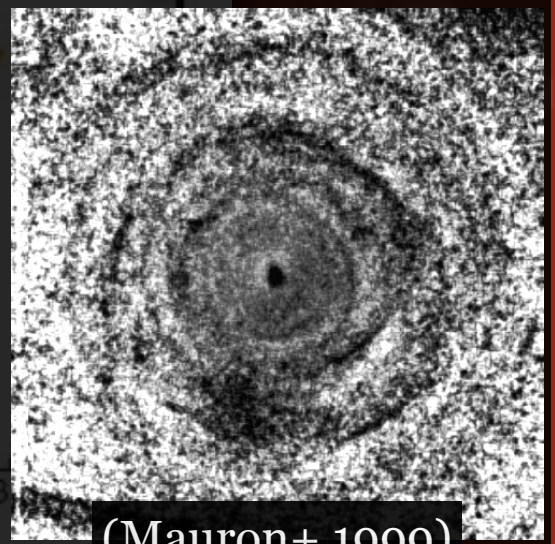
Shell Morphologies

Spherical shell



(Herwig 2005)

IRC +10 216

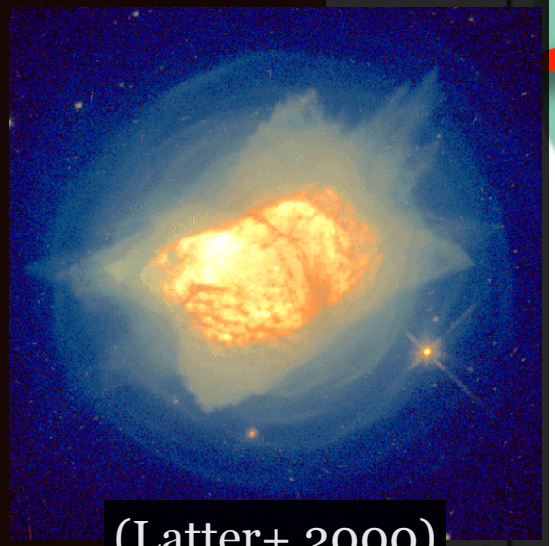


(Mauron+ 1999)

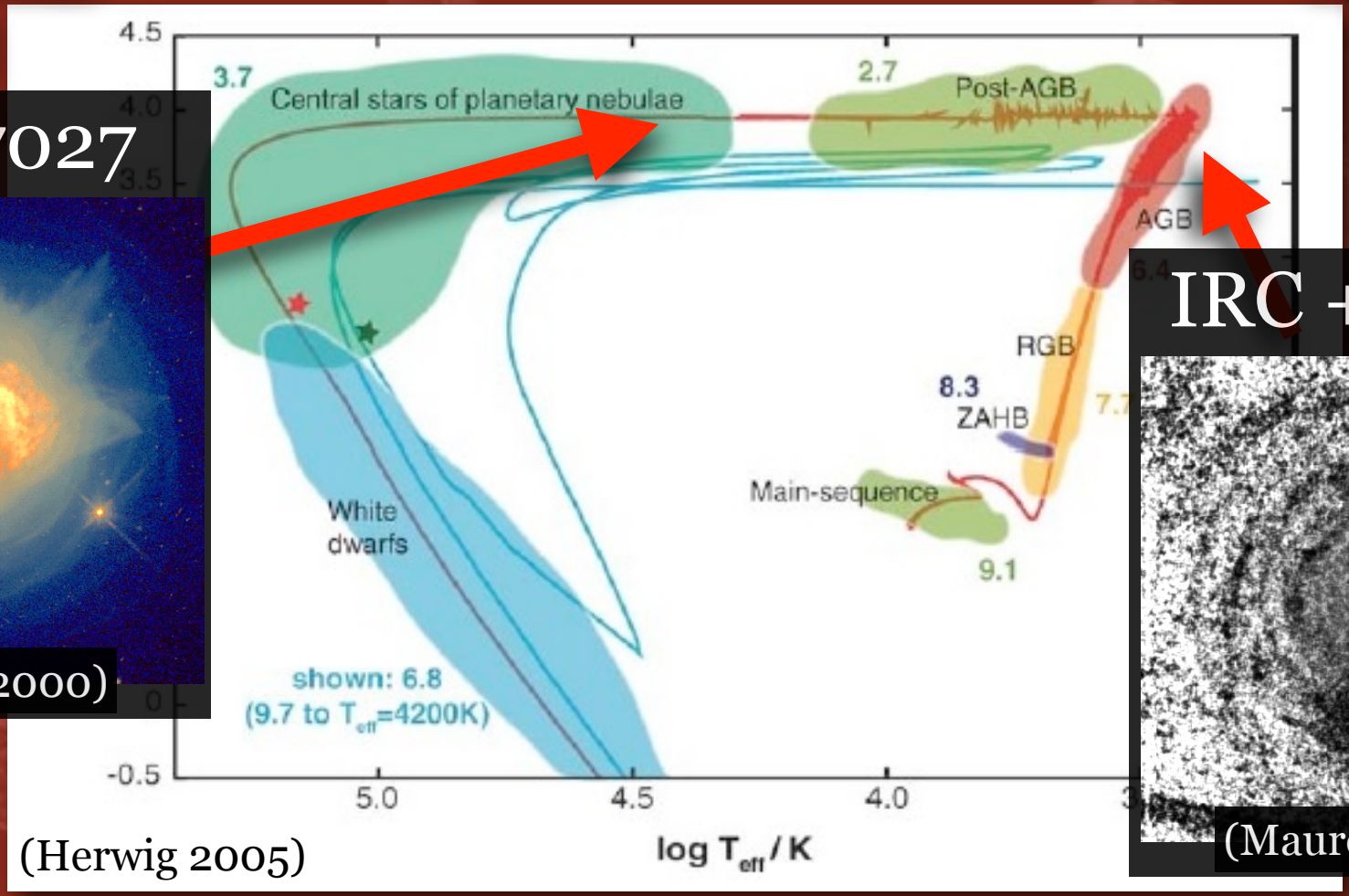
Shell Morphologies

Aspherical shell

NGC 7027



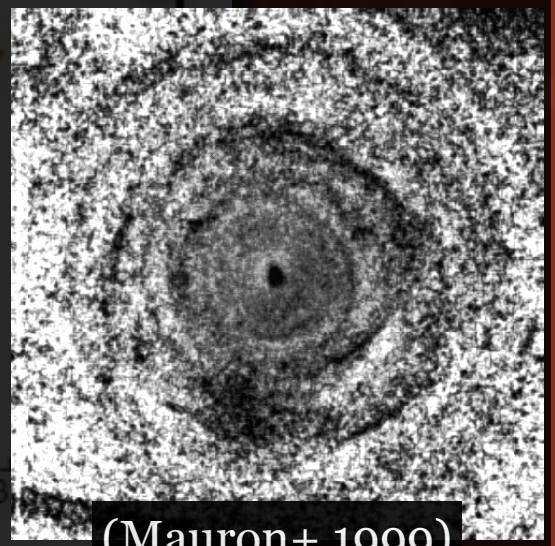
(Latter+ 2000)



(Herwig 2005)

Spherical shell

IRC +10 216



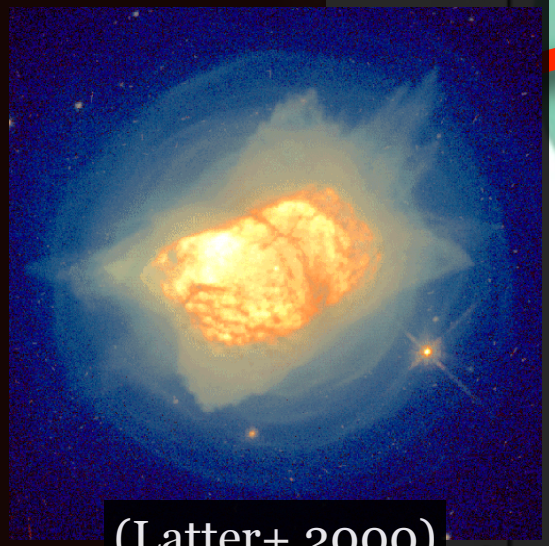
(Mauron+ 1999)

Shell Morphologies

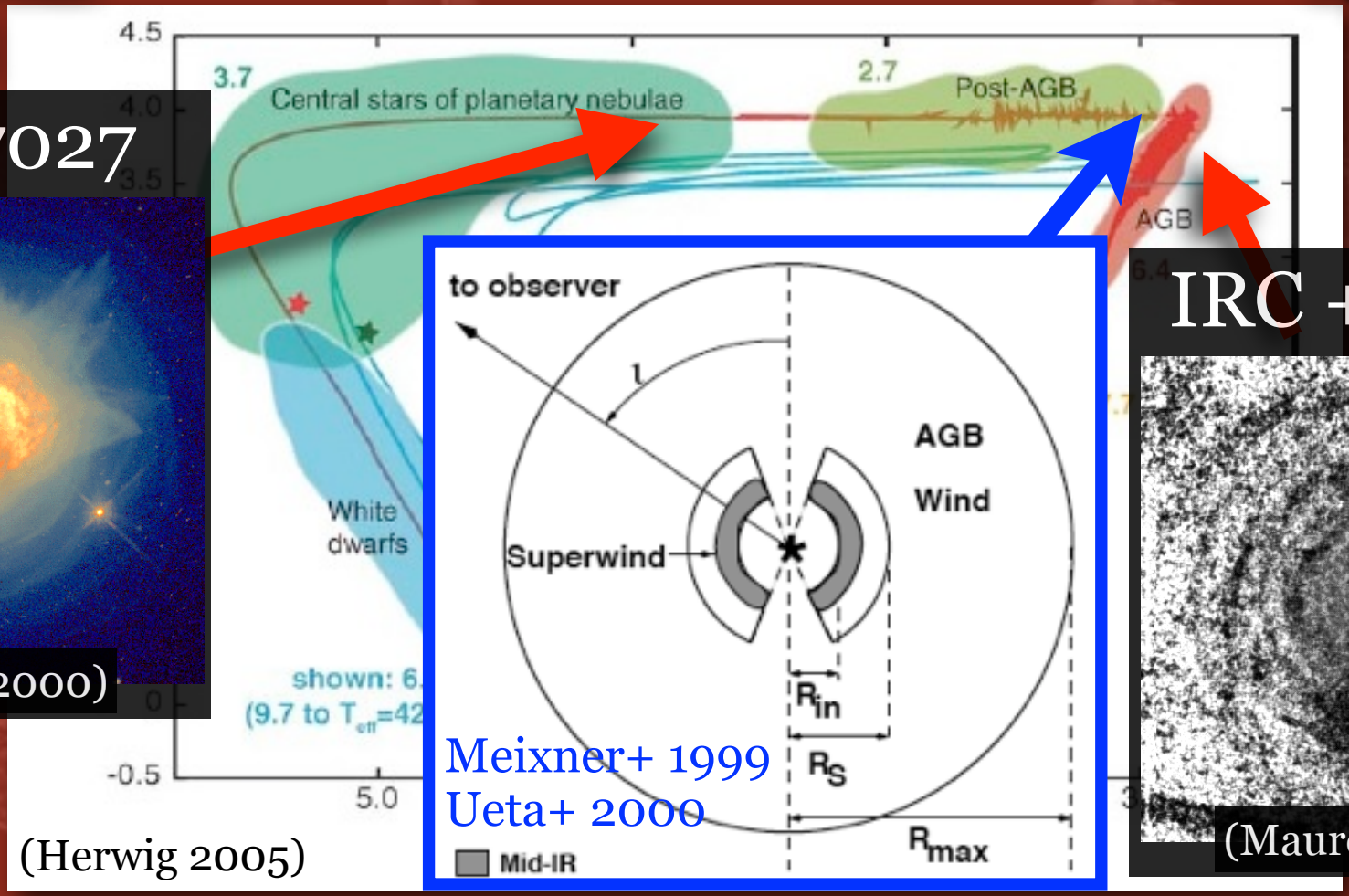
Aspherical shell

Spherical shell

NGC 7027

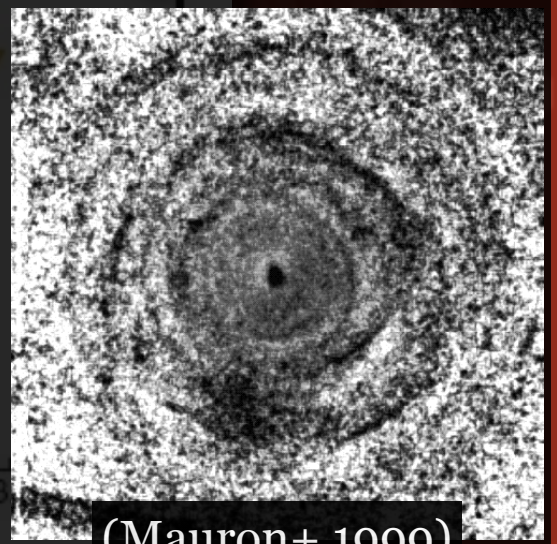


(Latter+ 2000)



(Herwig 2005)

IRC +10 216

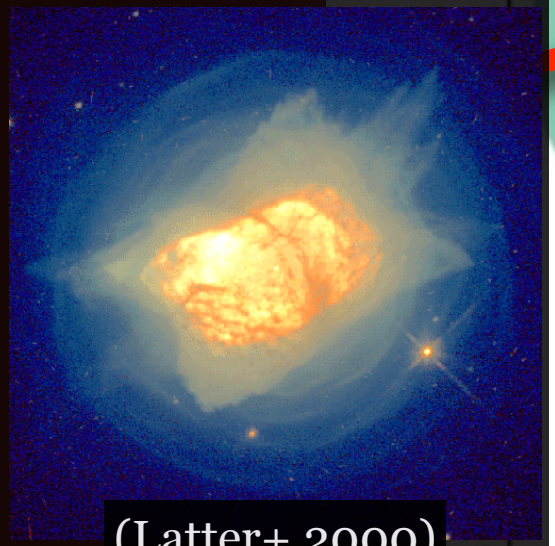


(Mauron+ 1999)

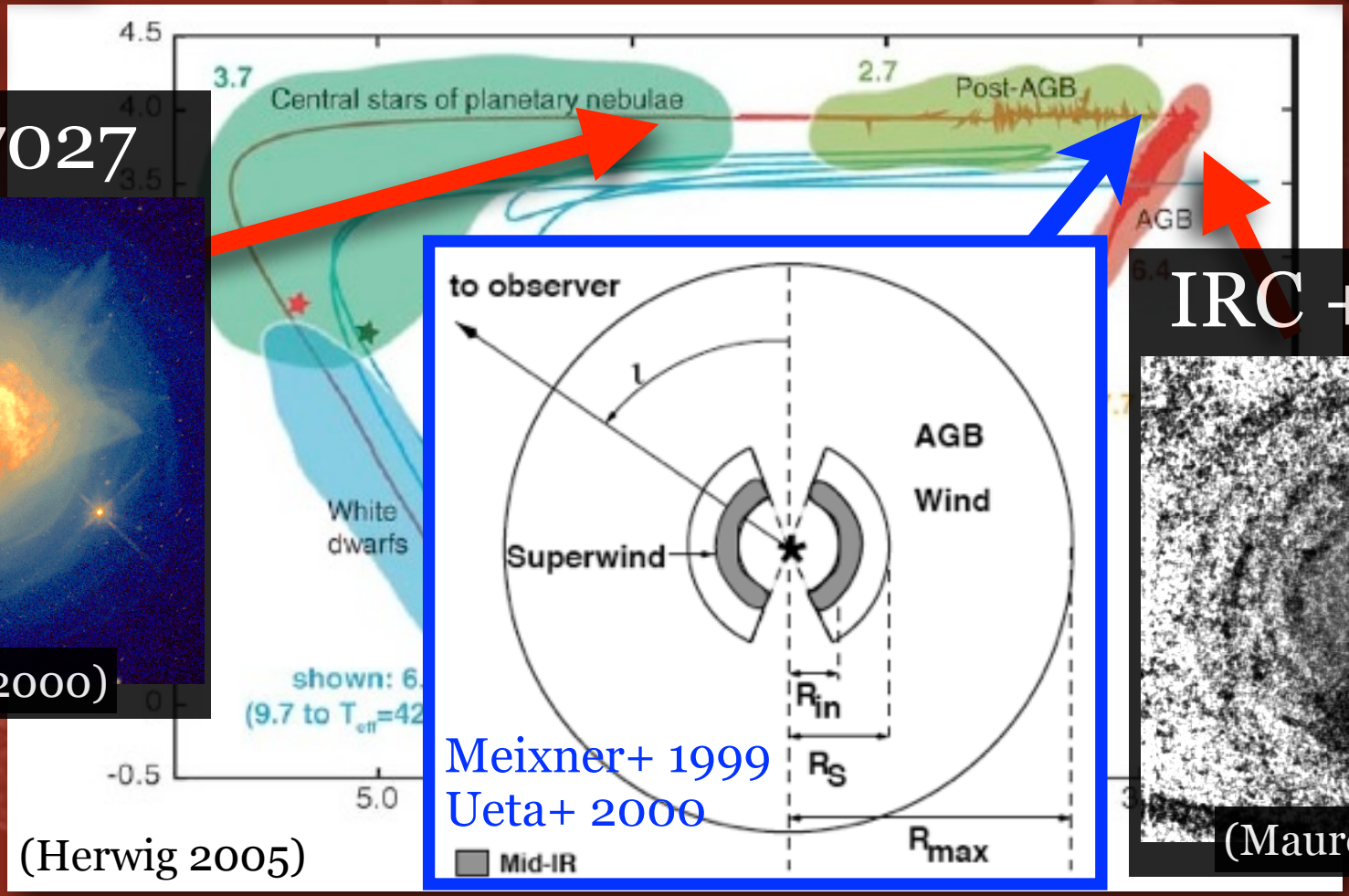
Shell Morphologies

Aspherical shell

NGC 7027



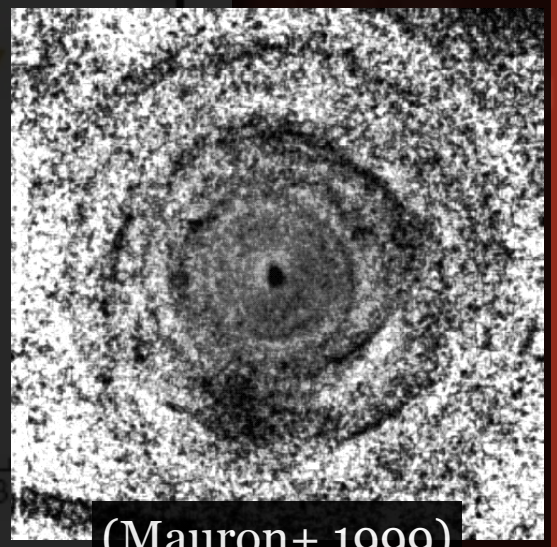
(Latter+ 2000)



(Herwig 2005)

Spherical shell

IRC +10 216

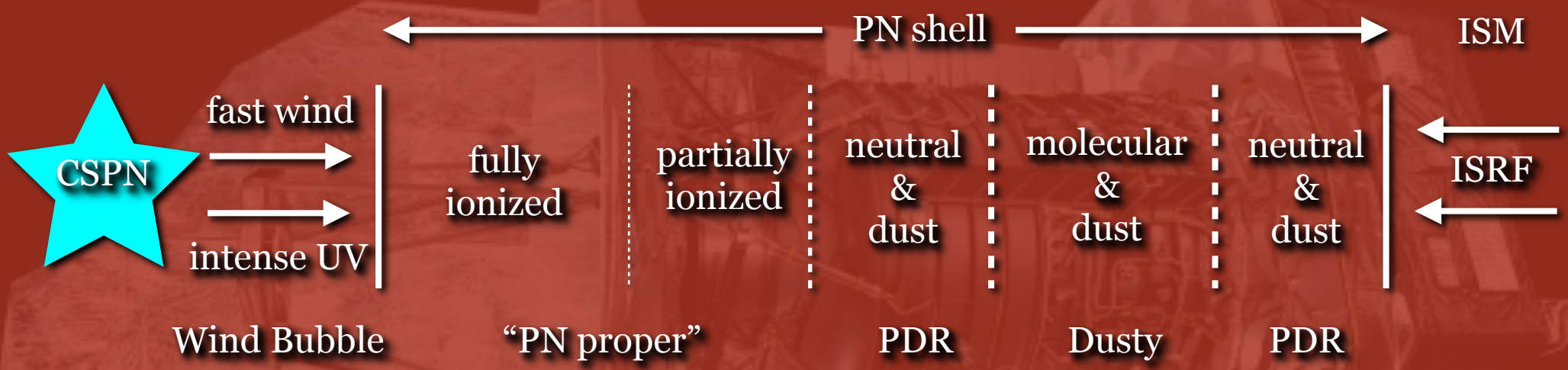


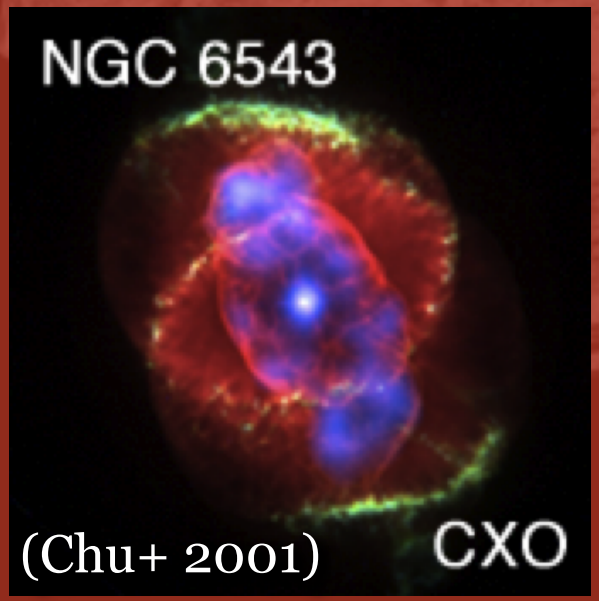
(Mauron+ 1999)

Look for the "fossil records" in extended shells

Look for the "onset" in AGB stars/PPNs

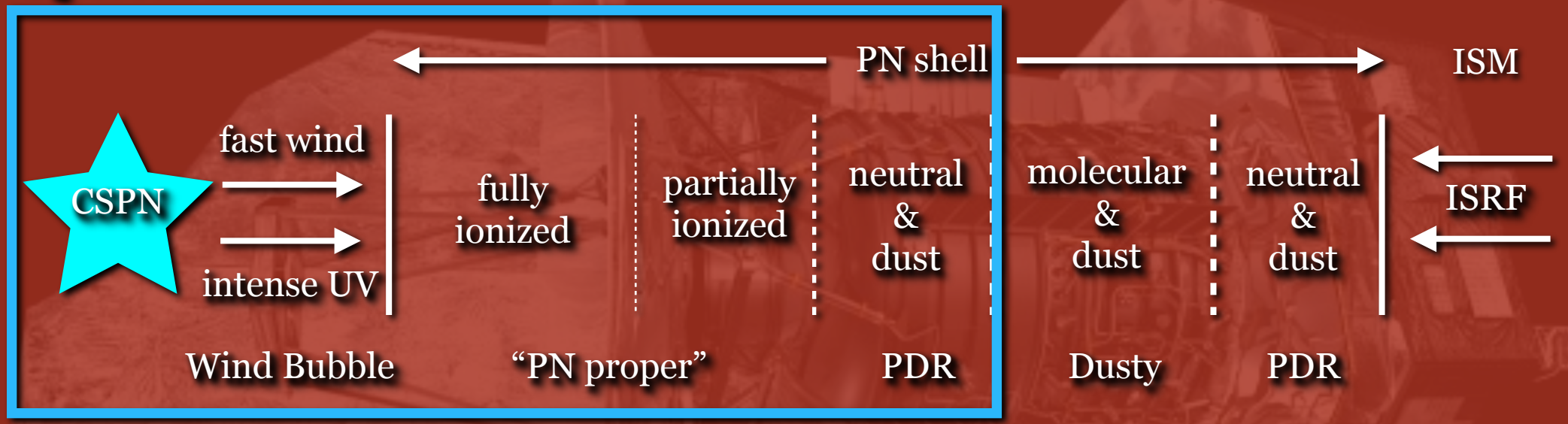
PNs as Gas-Dust Dynamical Systems

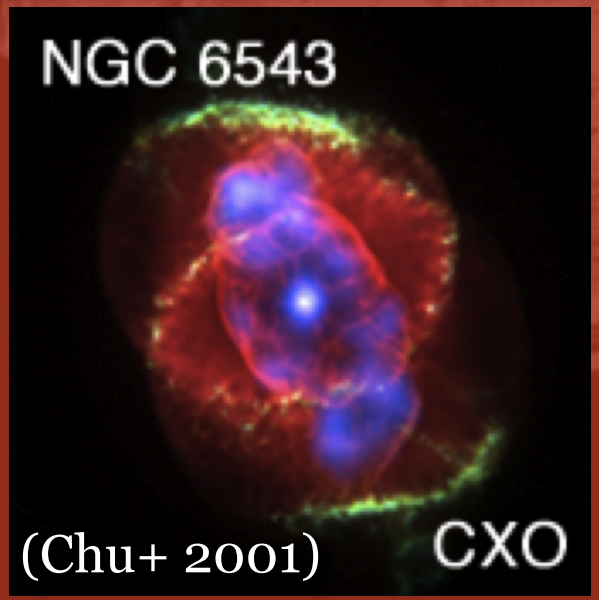




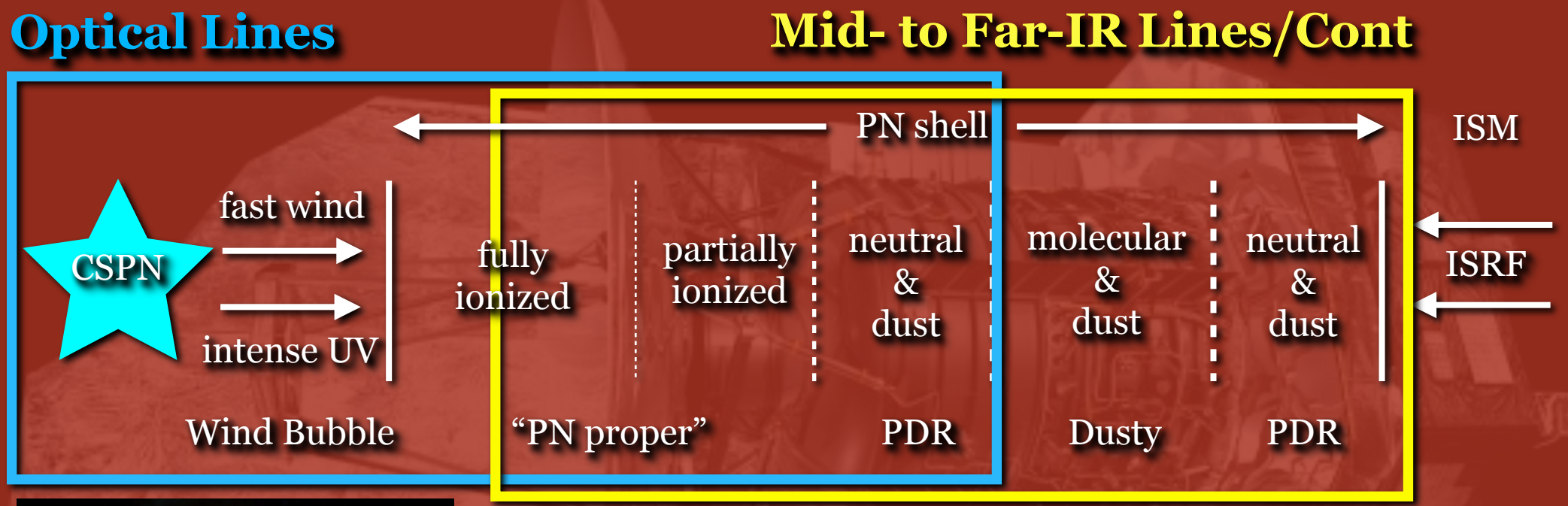
PNs as Gas-Dust Dynamical Systems

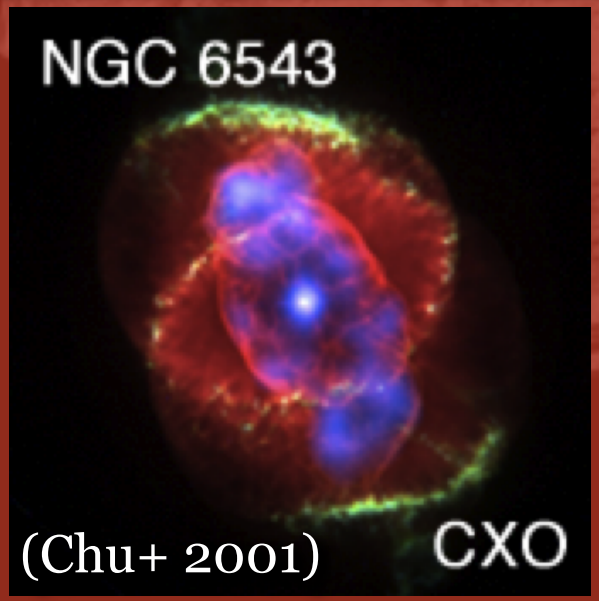
Optical Lines



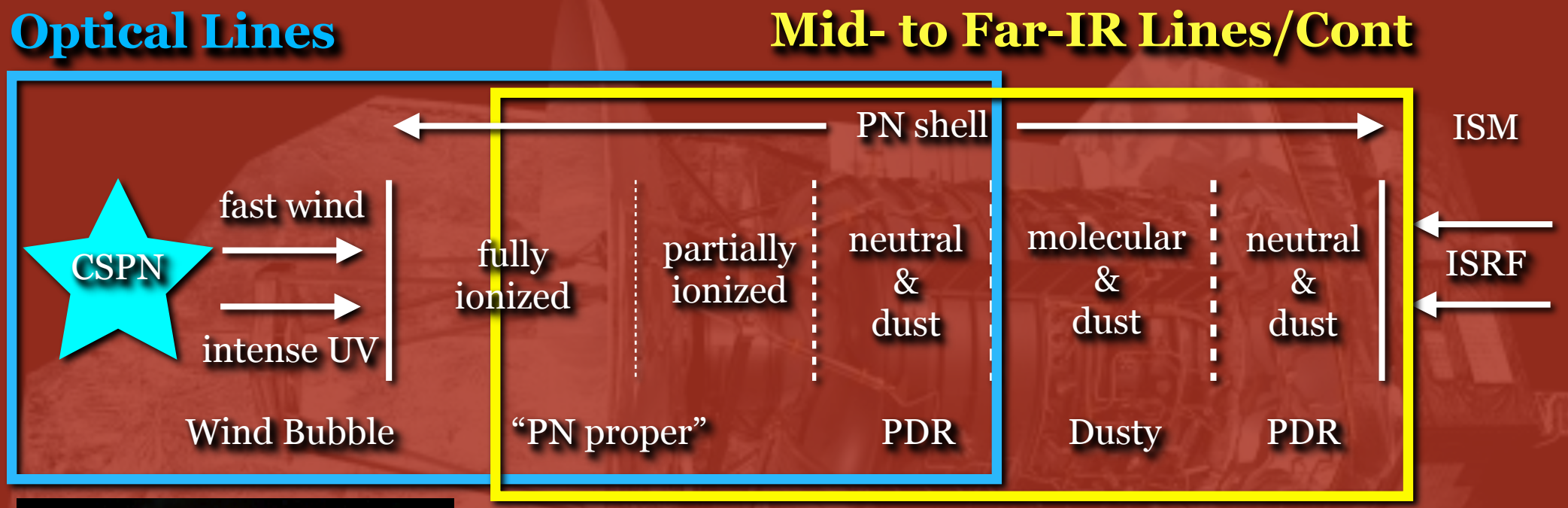


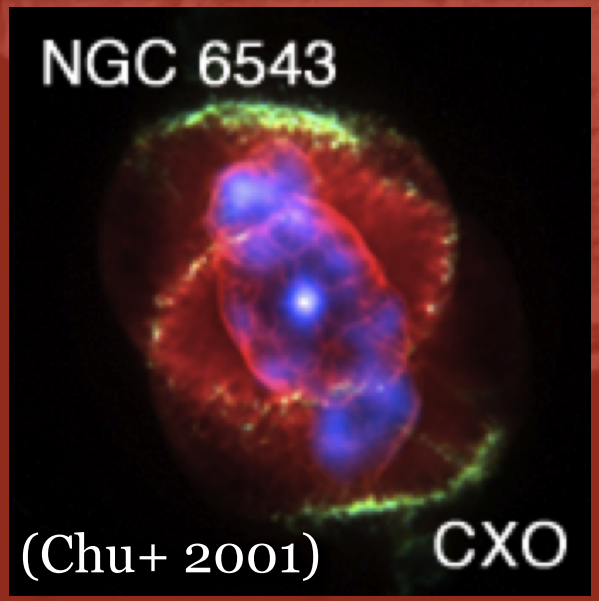
PNs as Gas-Dust Dynamical Systems





PNs as Gas-Dust Dynamical Systems

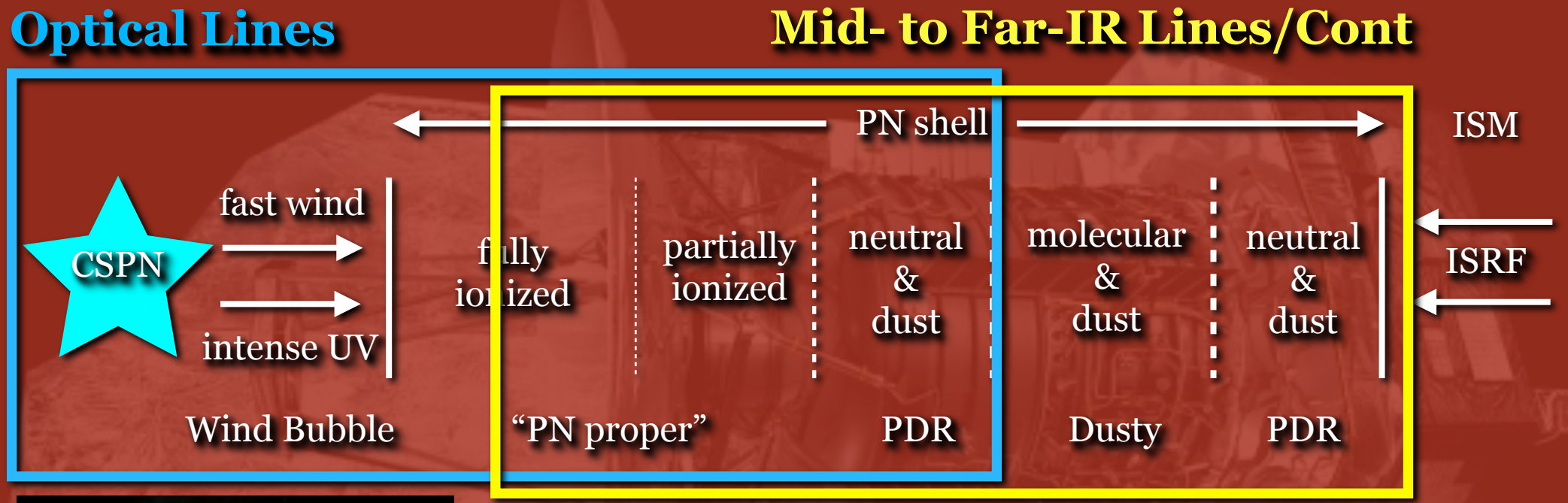


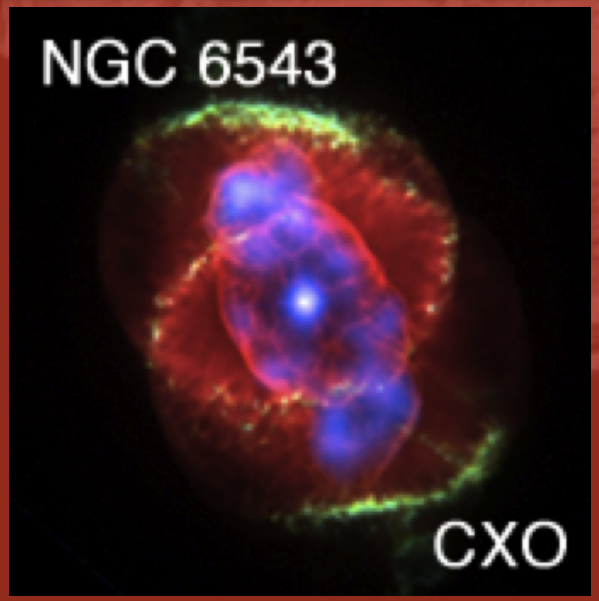


PNs = Relatively isolated objects

Good to pin-down stratification (mass loss histories & mass budget) in spatially-resolved manner with less extinction

Gas-to-Dust Mass Ratio





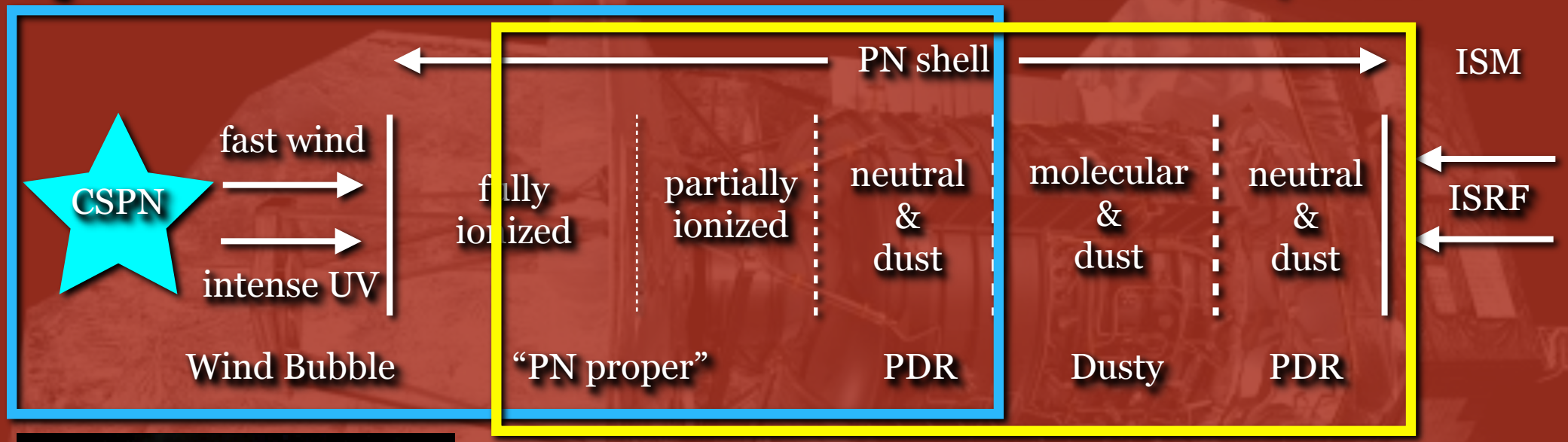
Gas component

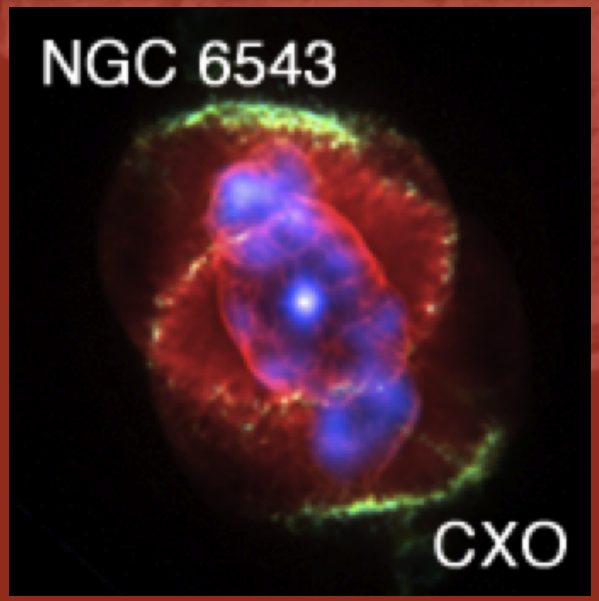
Gas-to-Dust Mass Ratio

Dust component

Gas-to-Dust Mass Ratio

Optical Lines **Mid- to Far-IR Lines/Cont**





Observe ⇐ Gas component

⇓

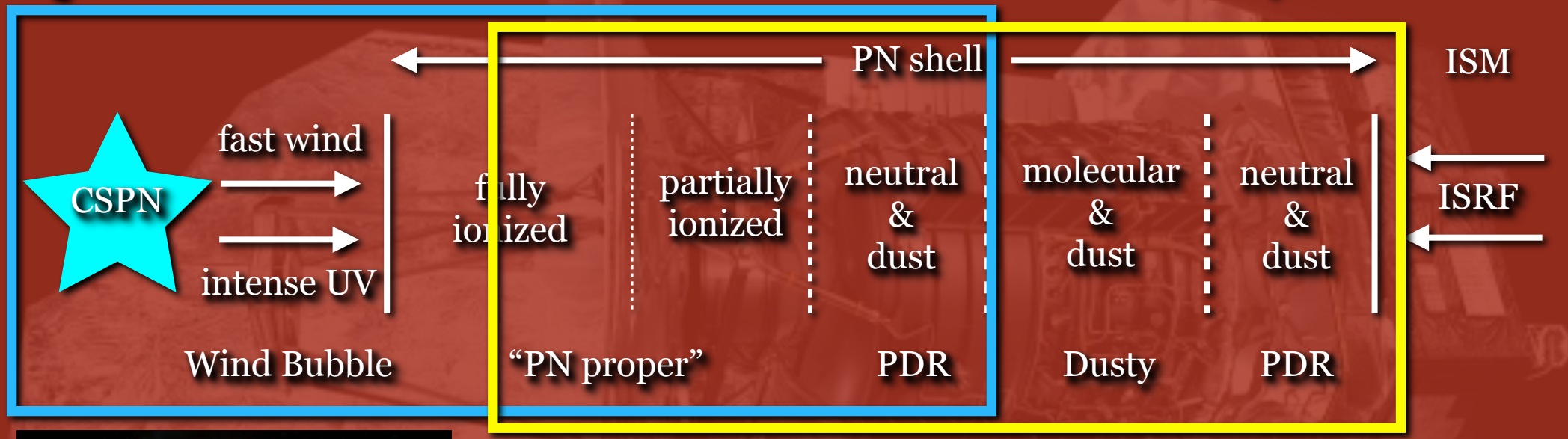
Gas-to-Dust Mass Ratio

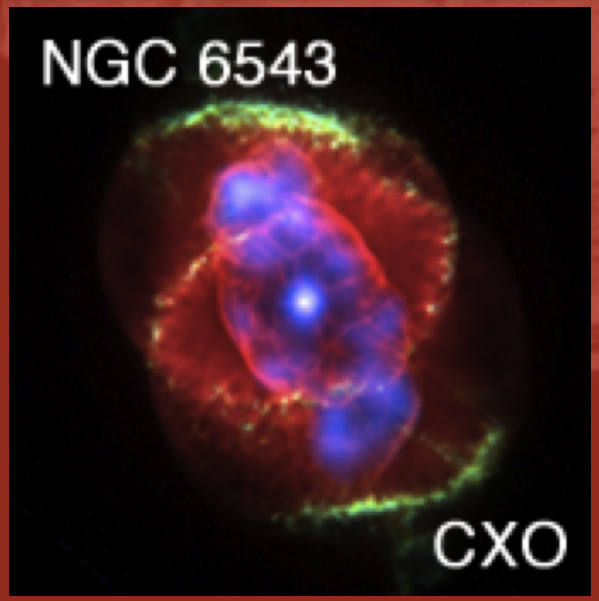
⇓

Infer ⇒ Dust component

Gas-to-Dust Mass Ratio

Optical Lines **Mid- to Far-IR Lines/Cont**





Observe ⇐ Gas component ⇐ Infer

⇓ ⇑

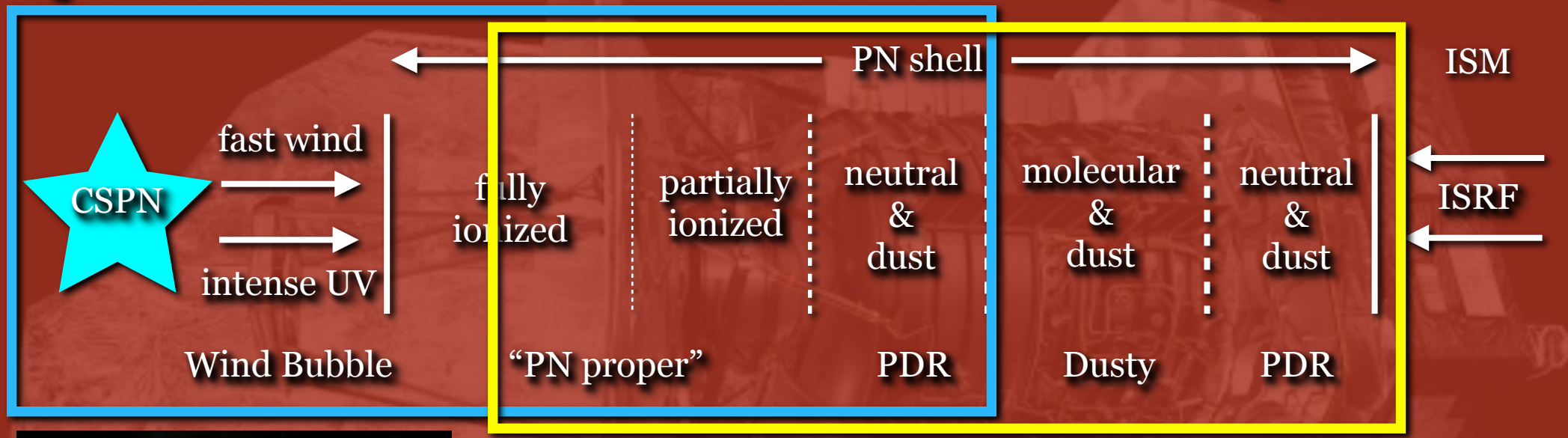
Gas-to-Dust Mass Ratio

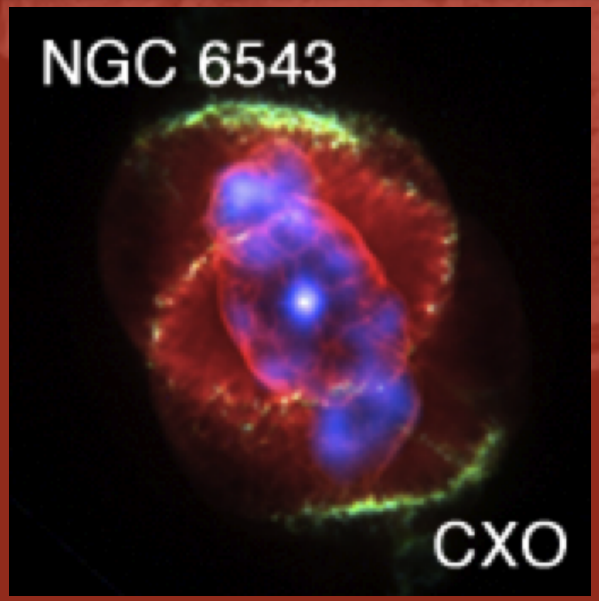
⇓ ⇑

Infer ⇒ Dust component ⇒ Observe

Gas-to-Dust Mass Ratio

Optical Lines **Mid- to Far-IR Lines/Cont**





Observe ⇐ Gas component ⇐ Infer

⇓ ⇑

Gas-to-Dust Mass Ratio

⇓ ⇑

Infer ⇒ Dust component ⇒ Observe

One value for an extended object?

Herschel Space Observatory

Launch: 5/14/2009

Last Obs: 4/29/2013

3.5 m diameter

3 instruments

- PACS:
  - 70, 100, 160 µm mapping
  - 51 - 220 µm 5×5 IFU spec
- SPIRE:
  - 250, 350, 500 µm mapping
  - 194 - 672 µm FTS spec
- HIFI:
  - 157 - 625 µm high-res spec

What is HerPlaNS?

Herschel Planetary Nebula Survey (HerPlaNS) is ...

- Open Time 1 program (92 AORs, ~200 hrs [3rd largest])
- To investigate spatial variations of
  - thermal continuum (dust grains)
  - far-IR lines (ionic, atomic, & molecular gas)
  - $T_{\rm dust}$, $M_{\rm dust}$, $T_{\rm e}$, $n_{\rm e}$, ionic/elemental abundances

  via broadband mapping @ 70, 160, 250, 350, 500μm & multi-position spectroscopy @ 51 - 672μm
- Partnered with Chandra Planetary Nebula Survey (ChanPlaNS; Kastner+ 2012)

Collaborators

PI: Toshiya Ueta (U. of Denver)

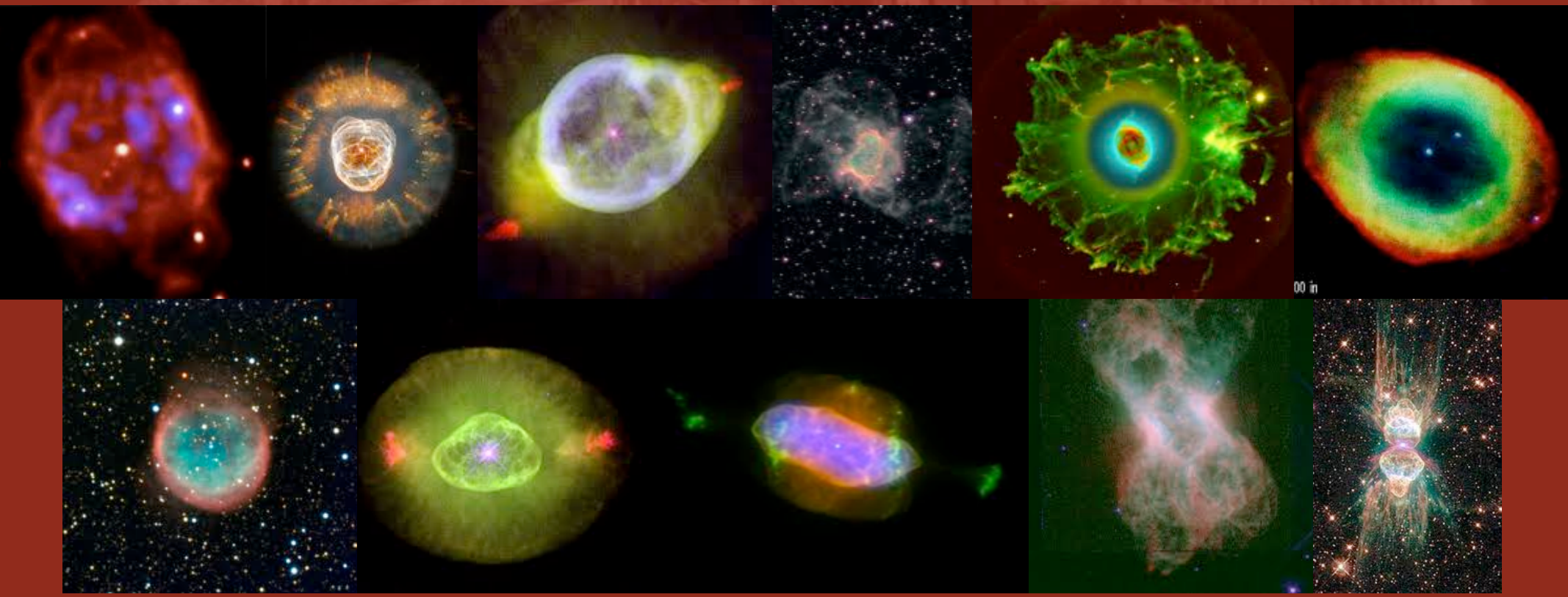
D. Ladjal (U. of Denver), K. M. Exter (KUL), M. Otsuka (ASIAA), I. Aleman (Leiden), R. Szczerba, N. Siodmiak (CAMK), J.H. Kastner (RIT), R. Montez (Vanderbilt), B. Balick (U. of Washington), E. Behar (Technion), E.G. Blackman (U. of Rochester), Y.-H. Chu (U. of Illinois), O. De Marco (Macquarie U.), K. Hebden (U. of Manchester), J.L. Hora (CfA), H. Izumiura (OAO/NAOJ), J.A. Lopez (UNAM), I. McDonald (Jodrell Bank), K. Murakawa (U. of Leeds), J. Nordhaus (RIT), R. Nordon (MPE), S. Ramstedt (Uppsala), R.E. Rattray (U. of Denver), R. Sahai (JPL), C. Sandin (AIP), A.G.G.M. Tielens (U. Leiden), P.A.M. van Hoof (ROB/KSB), E. Villaver (UAM), W. Vlemmings (Chalmers/Onsala), M. Wittkowski (ESO), I. Yamamura (ISAS/JAXA), A.A. Zijlstra (U. of Manchester)

Financial support from
NASA Herschel Science Center (NHSC)
Japan Society for the Promotion of Science

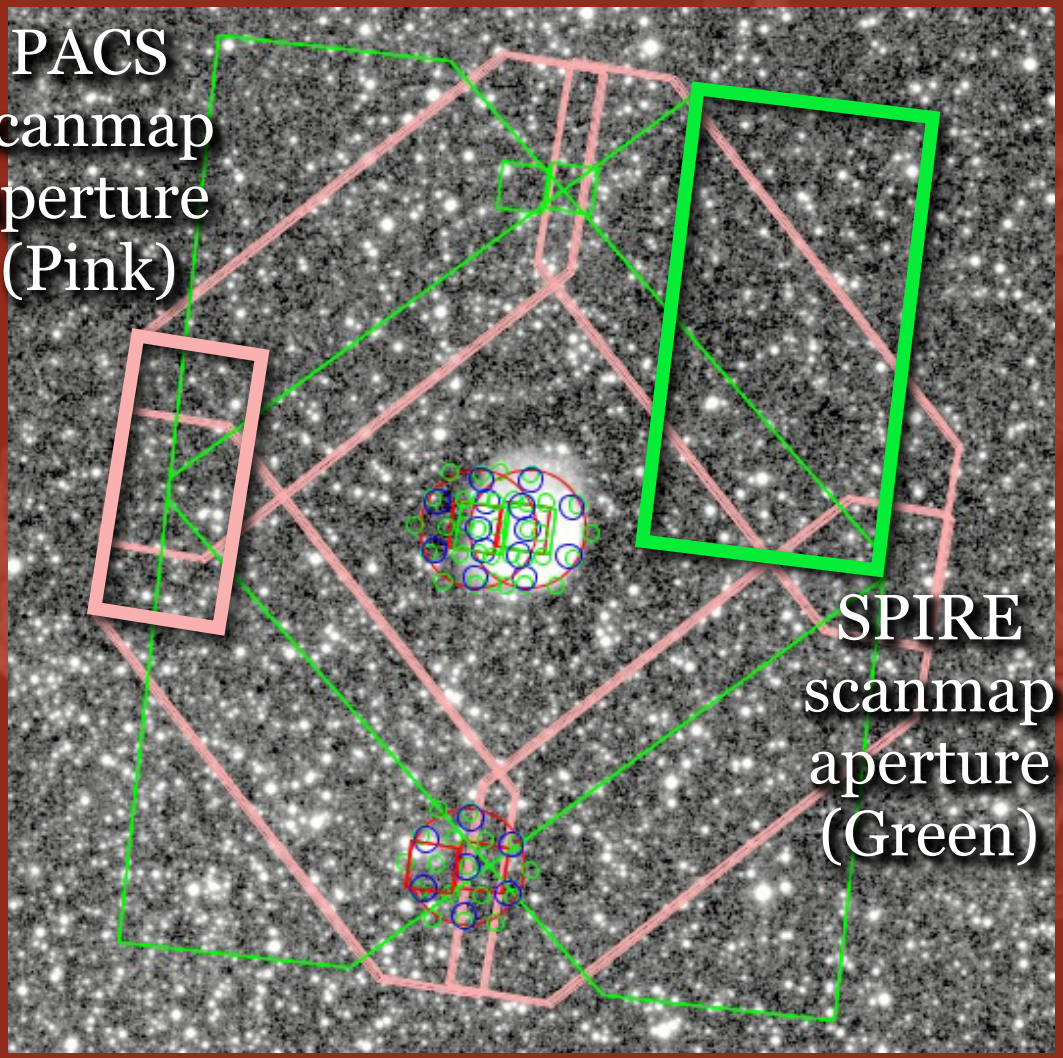
HerPlaNS Targets

- Total: 11 PNs

NGC 40, NGC 2392 (Eskimo), NGC 3242 (Ghost of Jupiter), NGC 6445, NGC 6543 (Cat's Eye), NGC 6720 (Ring), NGC 6781, NGC 6826, NGC 7009 (Saturn), NGC 7026, Mz 3 (Ant)



Mapping



NGC 6781

2 orthogonal
scans

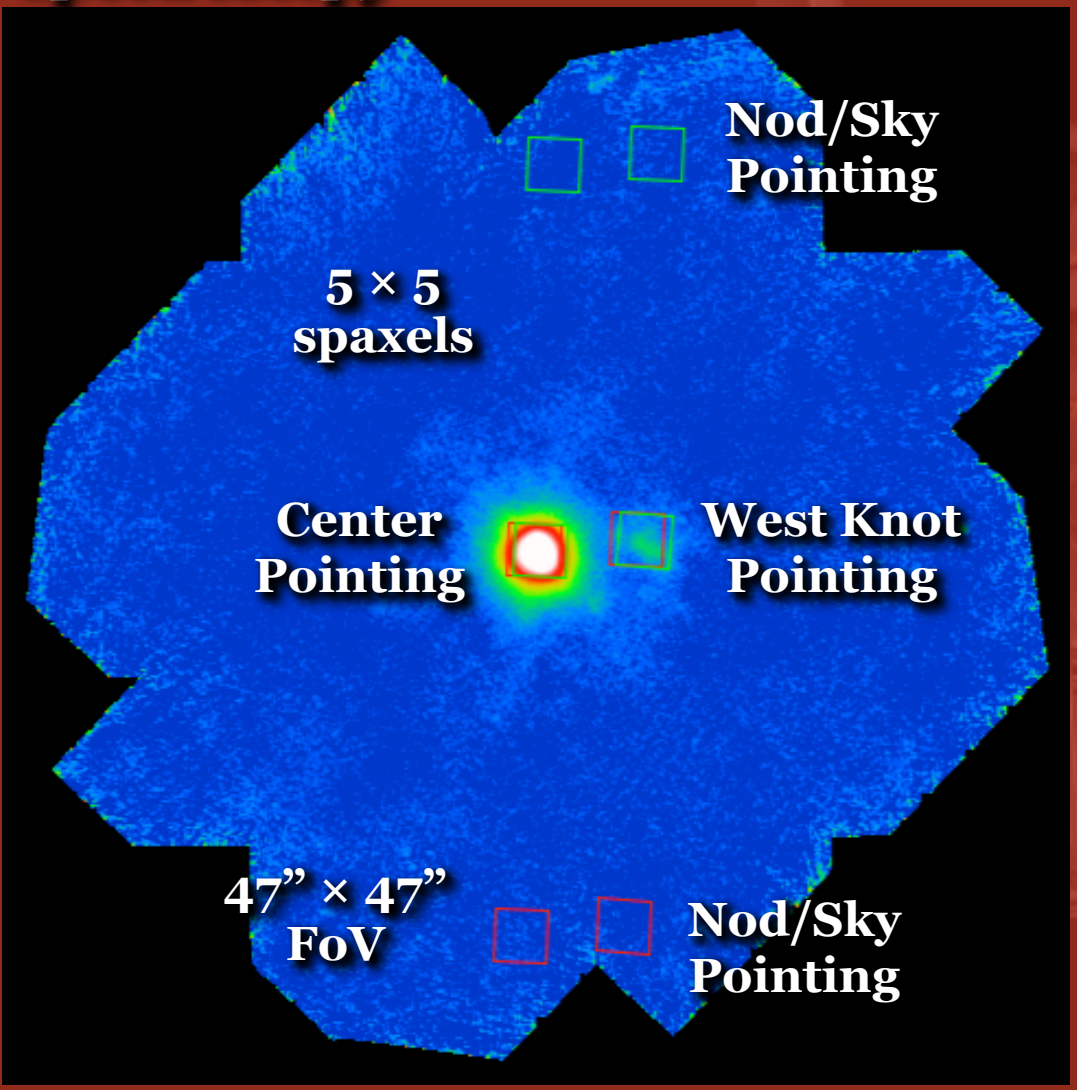
~10’ × 10’ Broadband maps
@ 70, 160, 250, 350, 500 μm

Beam size:
5.6, 6.8, 11.4, 18.2, 24.9, 36.3”

Pix scale:
1, 1, 2, 6, 9, 14”

Spectroscopy

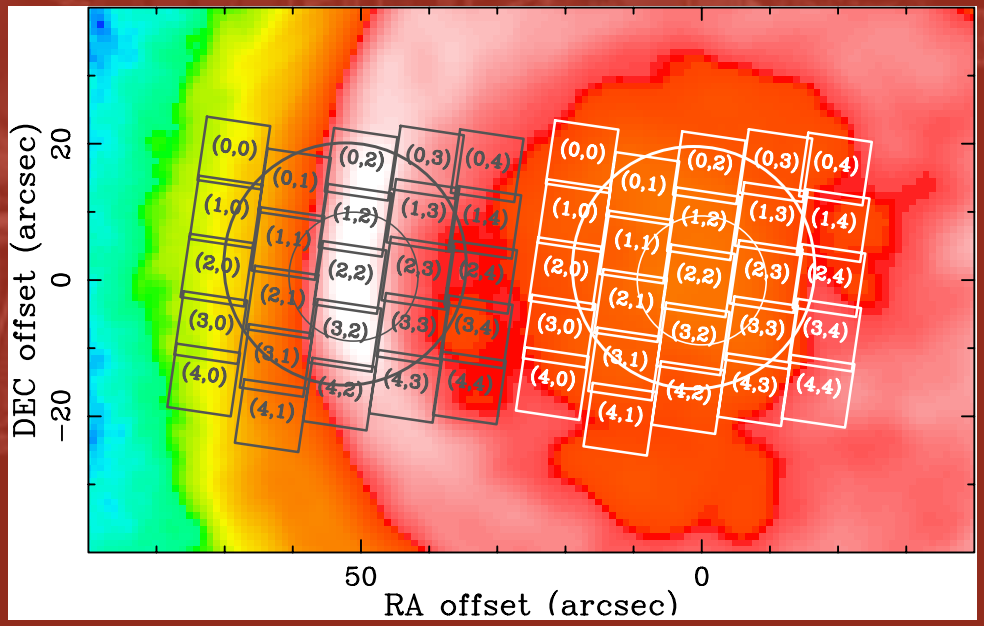
PACS IFU Spectroscopy



NGC 6543

5 × 5 IFU over 47” × 47”
(9.4” × 9.4” each)
@ 51 - 210 μm

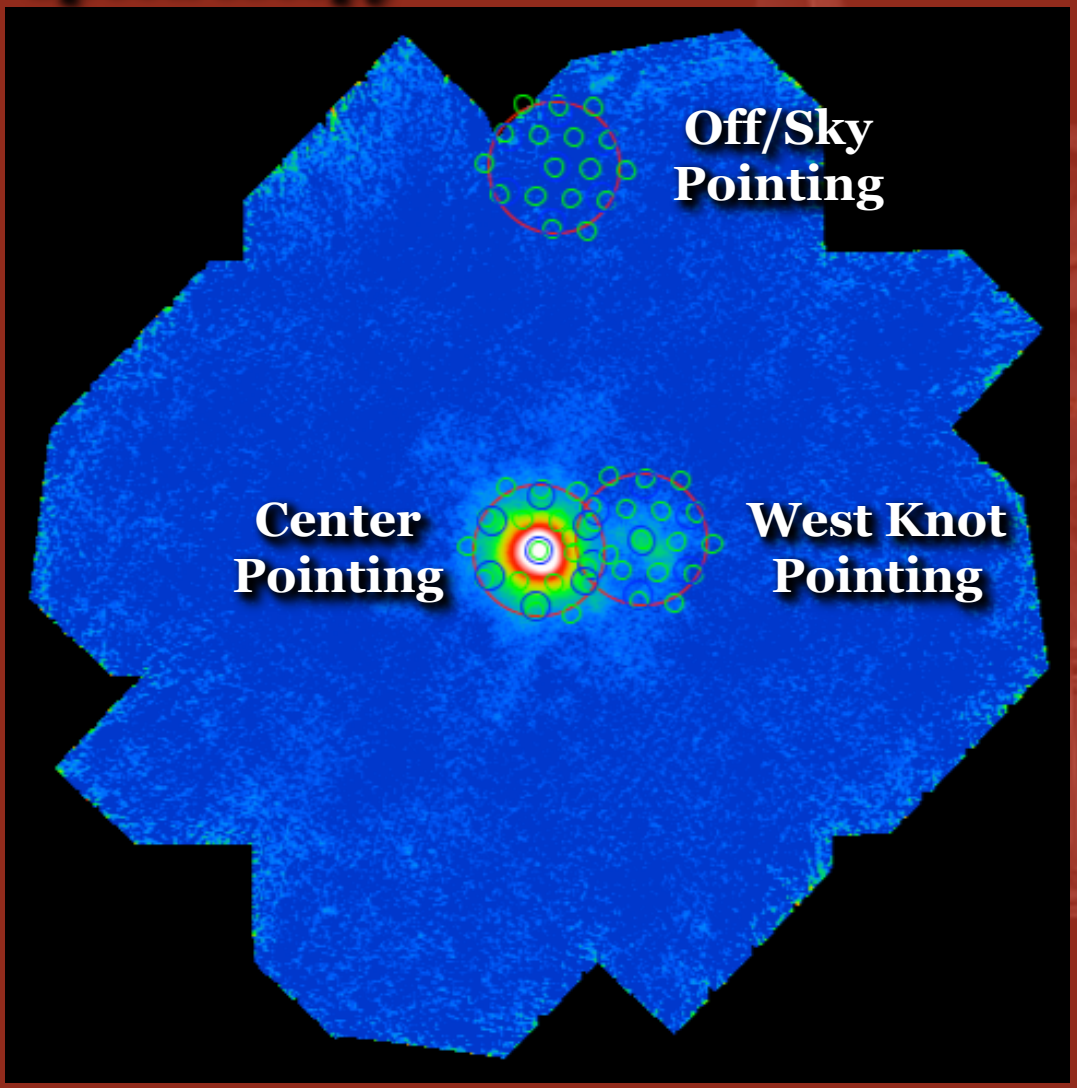
Beam size: 9.6” - 13.2”



NGC 6781

Spectroscopy

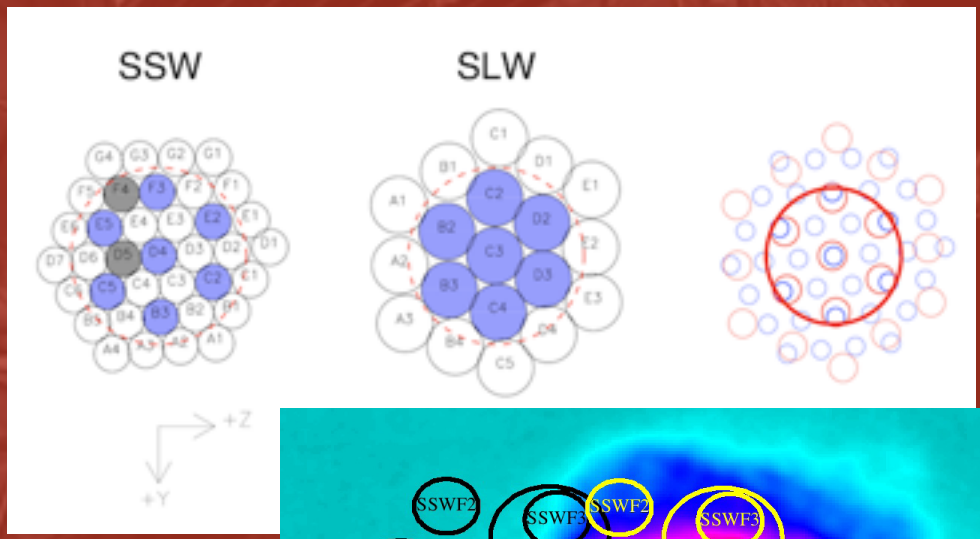
SPIRE FTS Spectroscopy

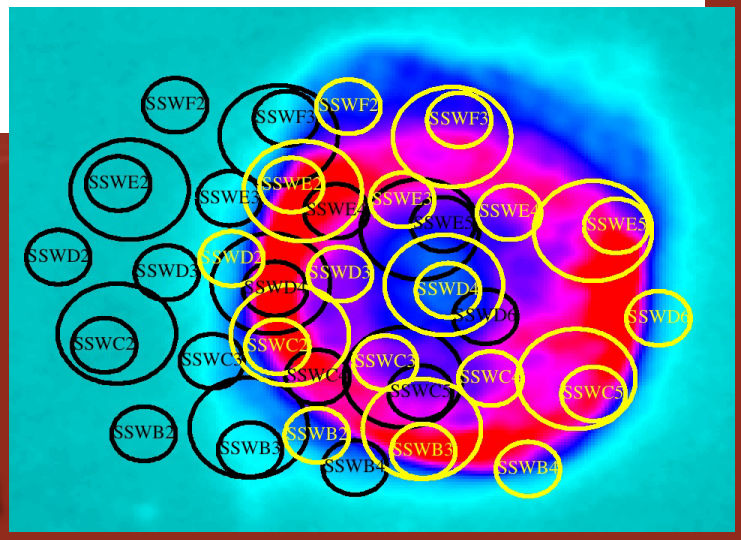


NGC 6543

SSW: 194 - 342 μm, 37 bolometers
SLW: 316 - 672 μm, 19 bolometers

Beam size:
SSW: 17” - 21” SLW: 29” - 42”





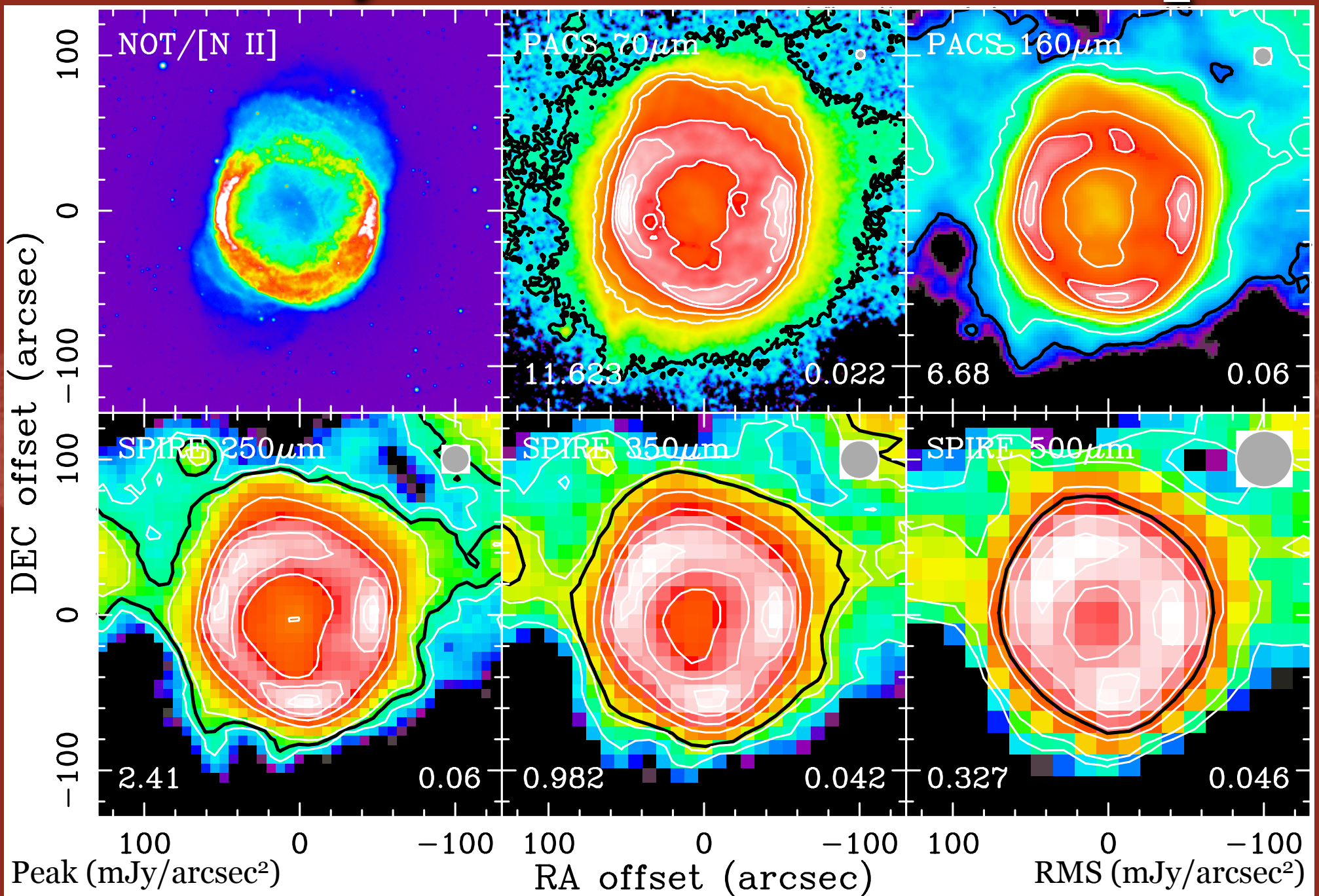
NGC 6781

HerPlaNS Data Products

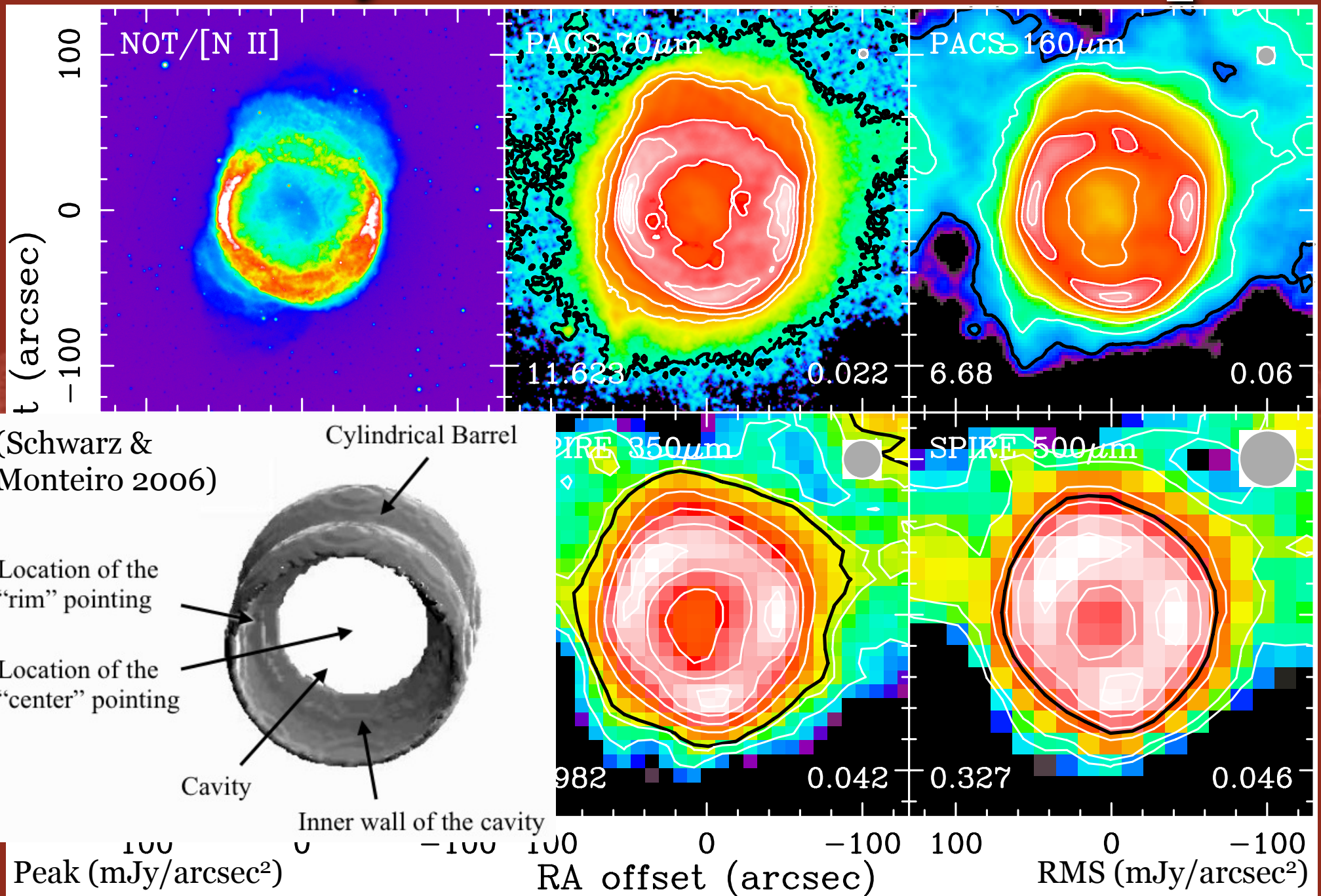
- 11 PNs (Ueta+ *submitted*)
- Broadband maps (55 total) (Ladjal+ *in prep*)
  - 5 bands @ 70, 160, 250, 350, & 500 μm
  - about <1 MJy/sr or <0.02 mJy/arcsec² RMS
- Spectra (2740 total) (Exter+ in *prep;* Rattray+ *in prep*)
  - PACS: 25×14 points, 51-210 μm, 4 mJy/arcsec² RMS
  - SPIRE:
    - 35×22 points, 194-342 μm, 2 mJy/arcsec² RMS
    - 19×22 points, 316-672 μm, 0.1 mJy/arcsec² RMS
    - 7+ per points, 194-672 μm

(Aleman+ *submitted*; Otsuka+ *in prep*)

NGC 6781 Broadband Maps

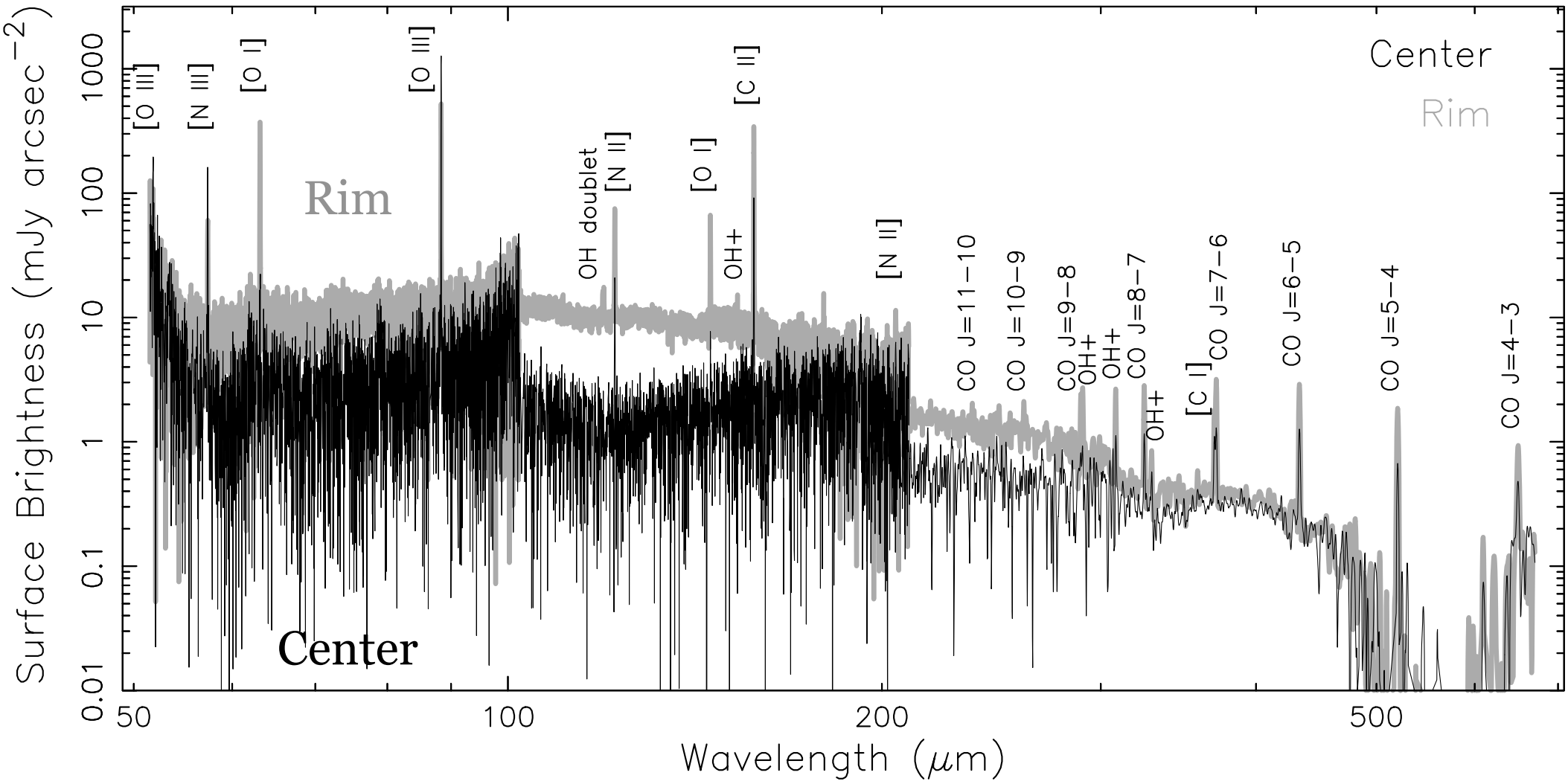


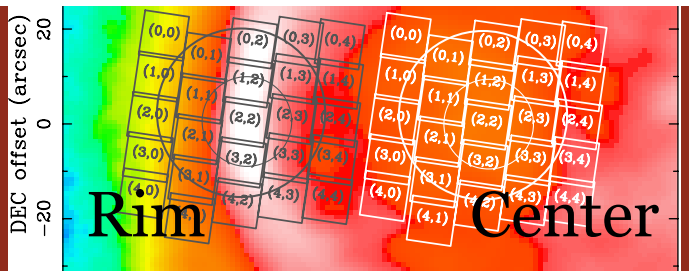
NGC 6781 Broadband Maps



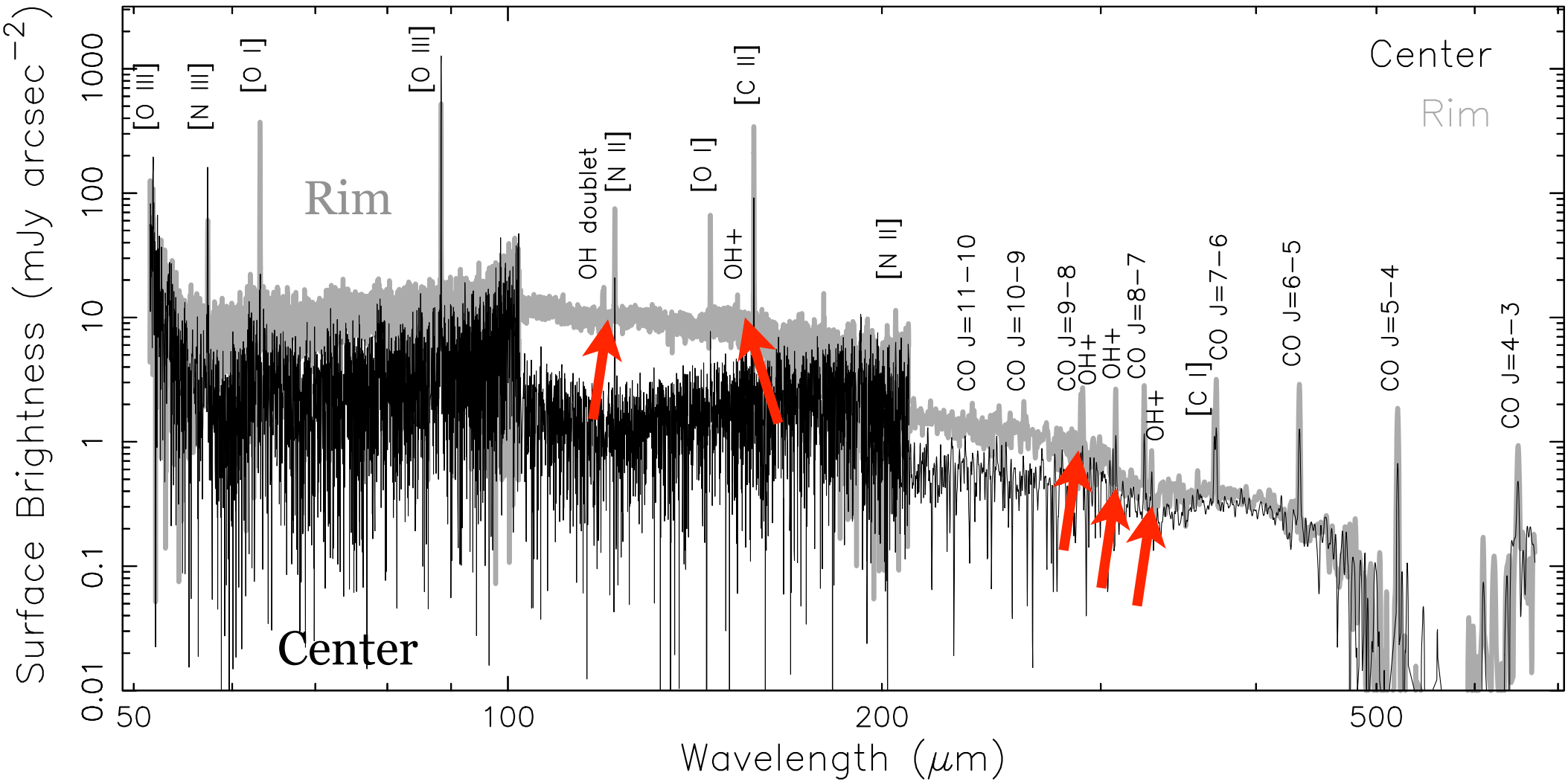
(Schwarz & Monteiro 2006)

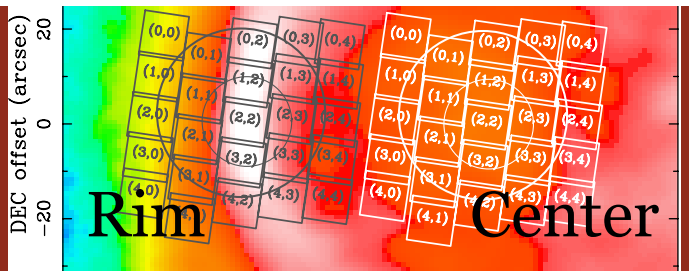
Full Spectrum



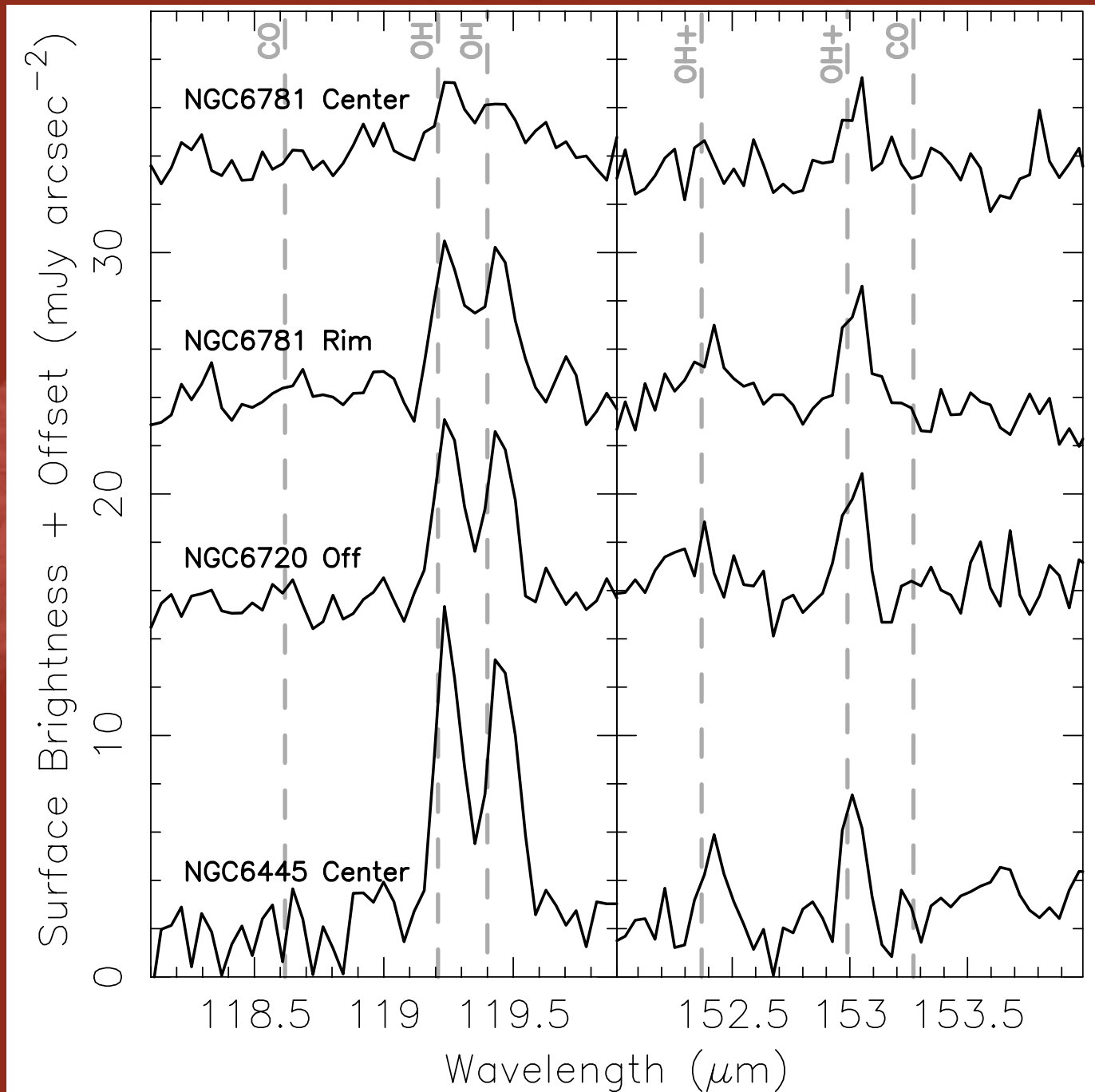


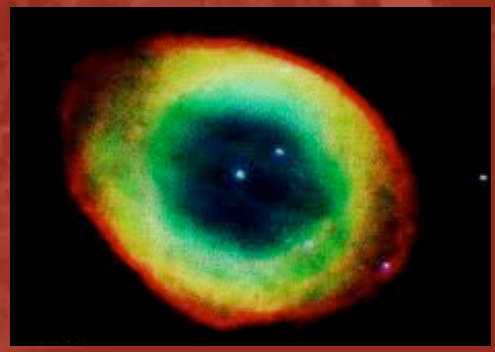
Full Spectrum

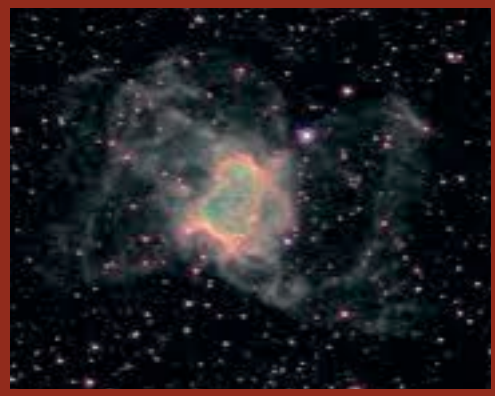




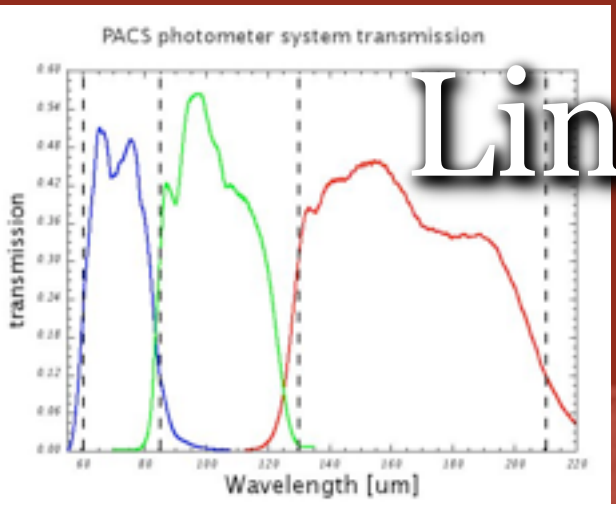
Detection of OH+



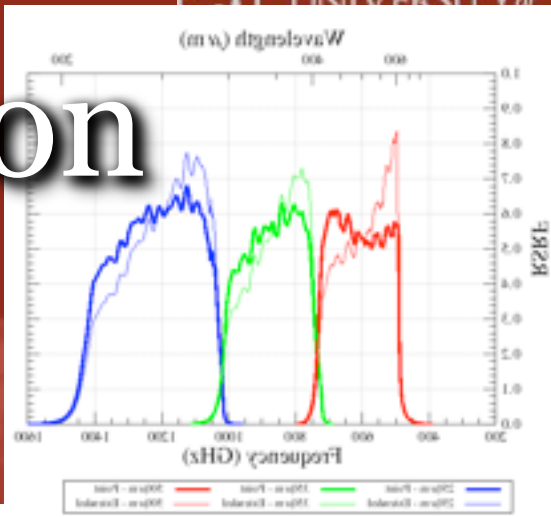


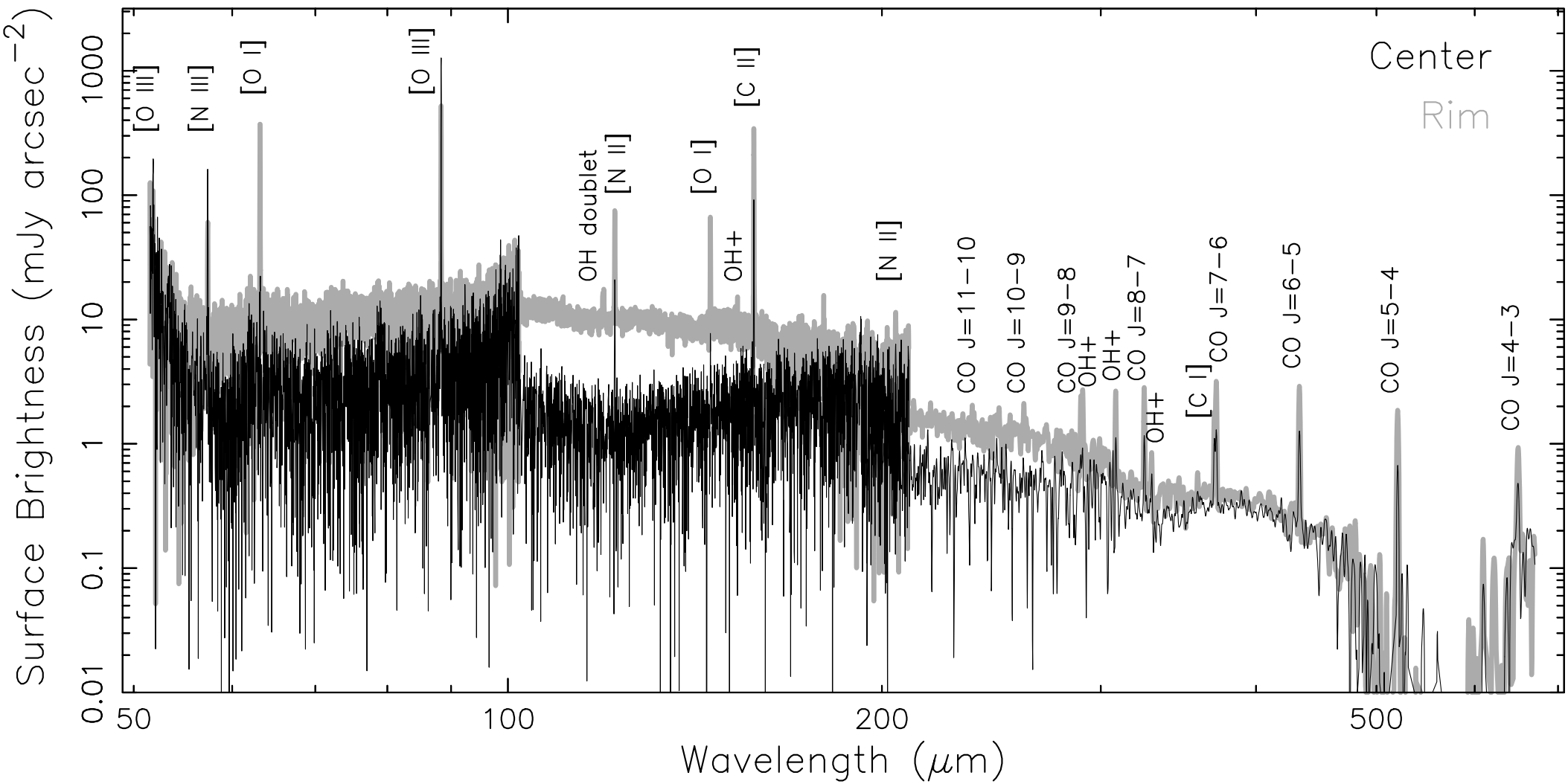


Line Contamination



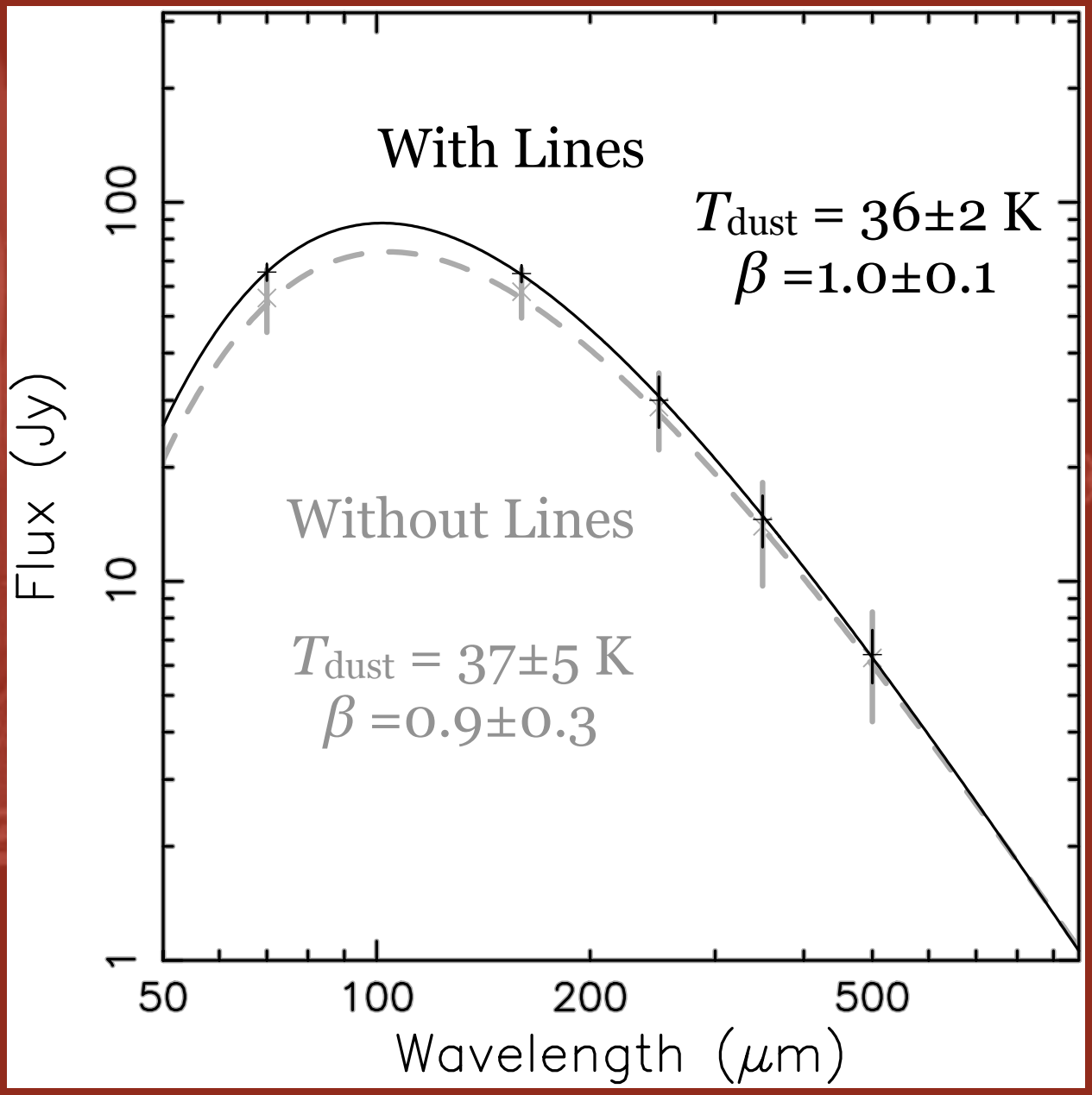
PACS SPIRE
Transmission
Curves



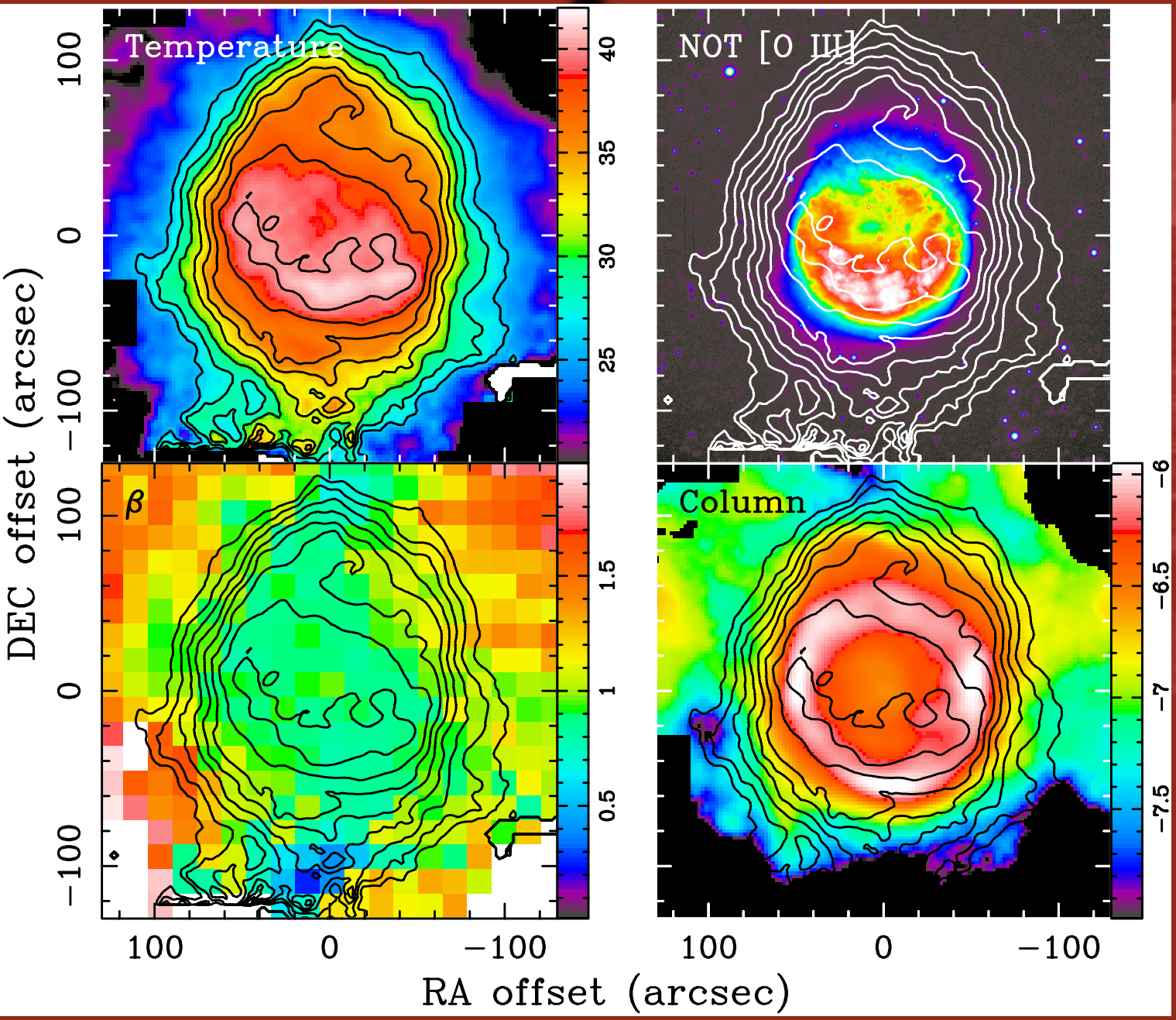


Line Contamination

- At most 8-20% difference in far-IR bands
- Practically no need to remove lines



Temperature Maps



$$I_\nu \propto \lambda^{-\beta} B_\nu(T_{\rm dust})$$

$T_{\rm dust}$ = 26-42 K

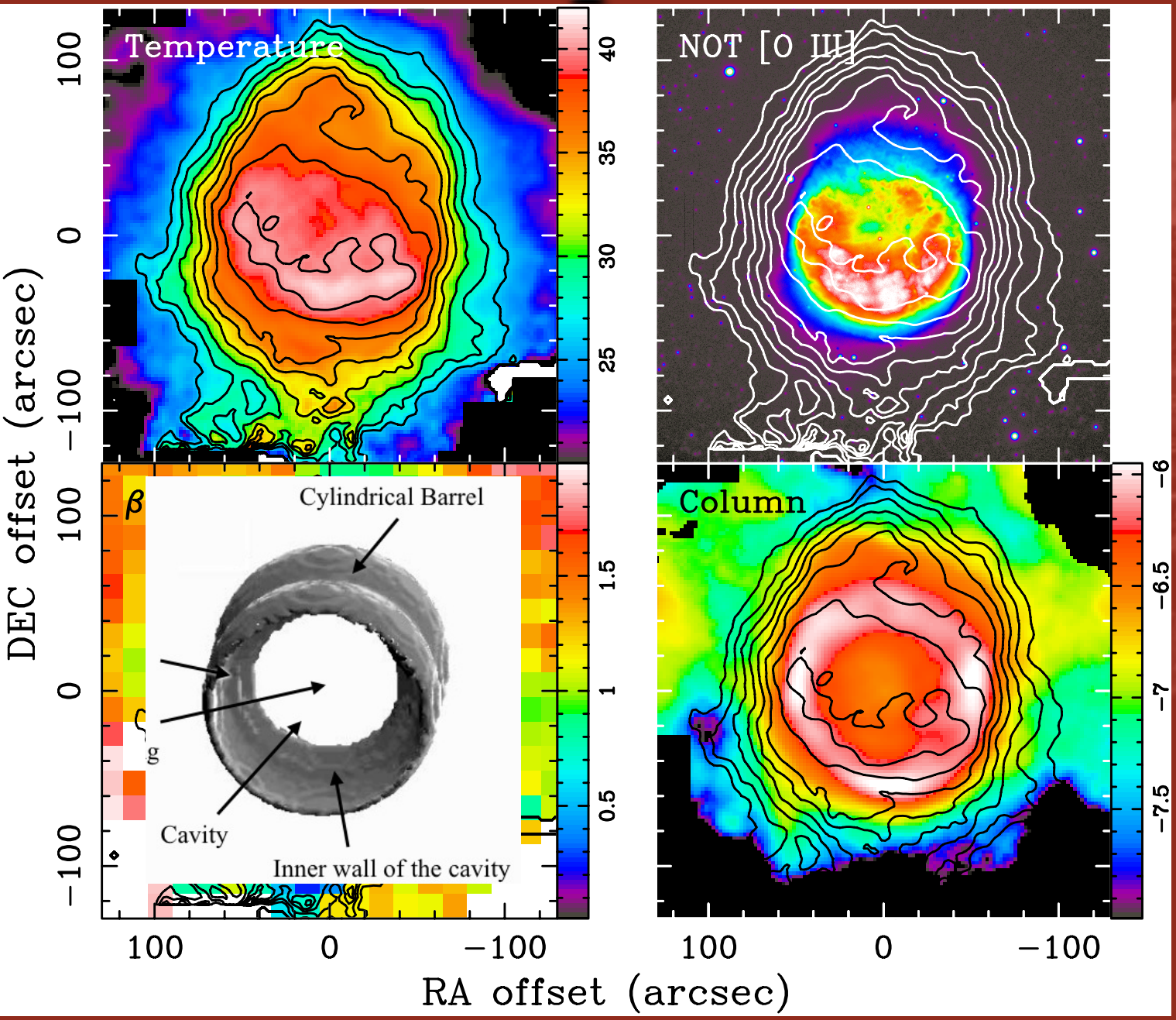
$\beta \sim 1$

$$\tau_\nu = -\ln\left(1 - \frac{I_\nu}{B_\nu(T_{\rm dust})}\right)$$

$$M_{\rm dust} = \frac{I_\nu D^2}{\kappa_\nu B_\nu(T_{\rm dust})}$$

$M_{\rm dust}$ = 0.004 $M_\odot$

Temperature Maps



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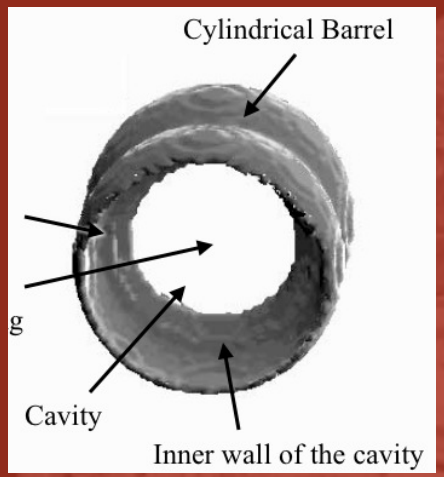
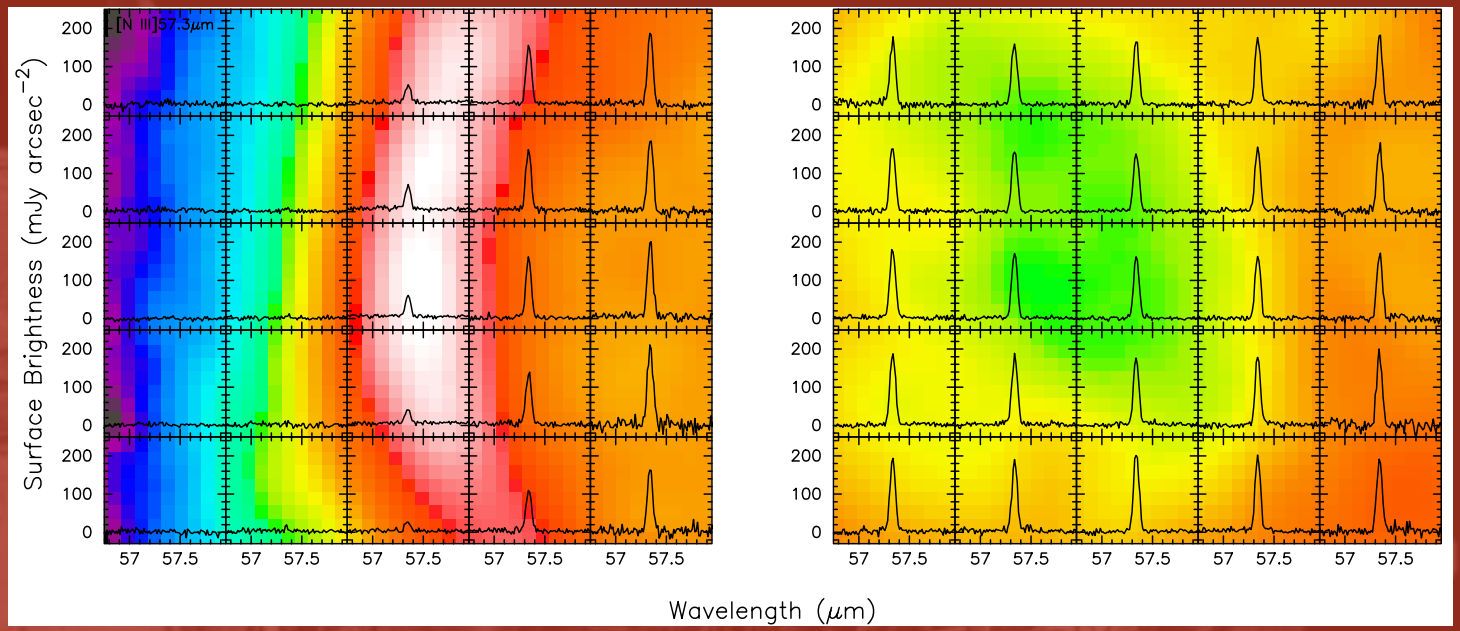
$M_{\rm dust}$ = 0.004 $M_\odot$

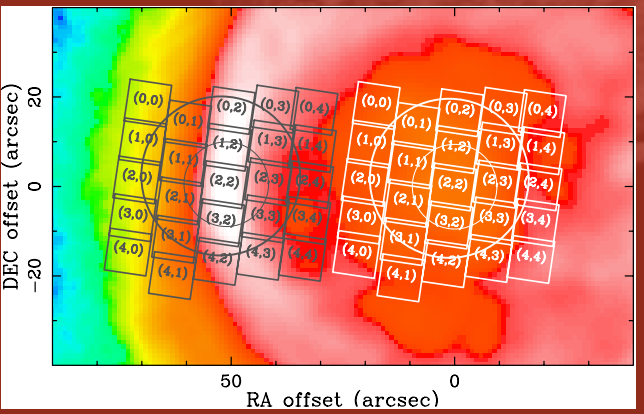
Fine-Structure Line Variations

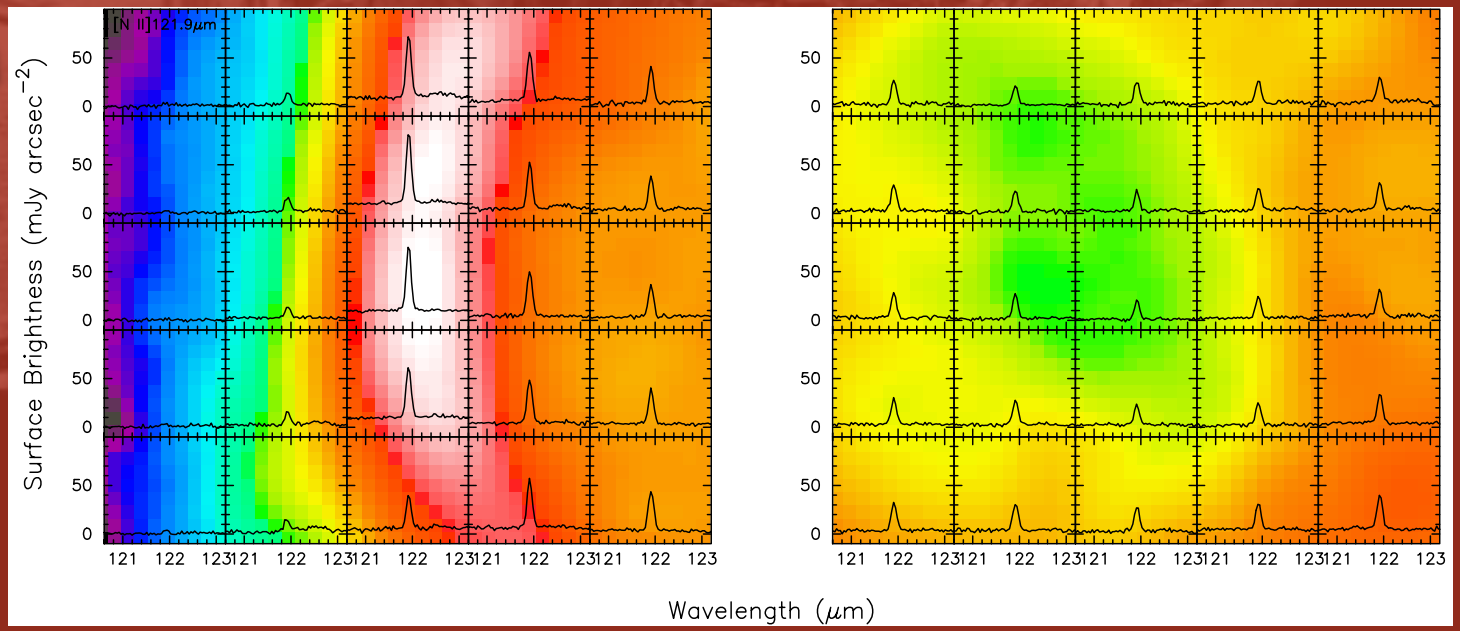
[N III] 57μm





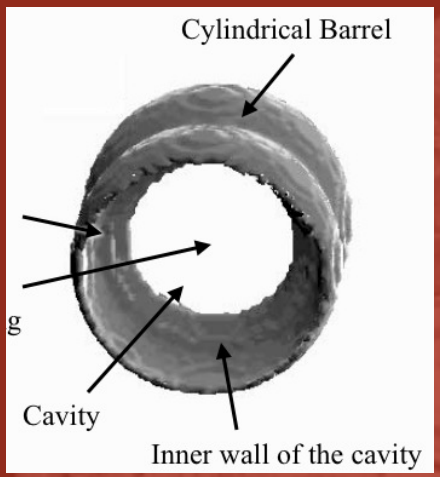
[N II] 122μm

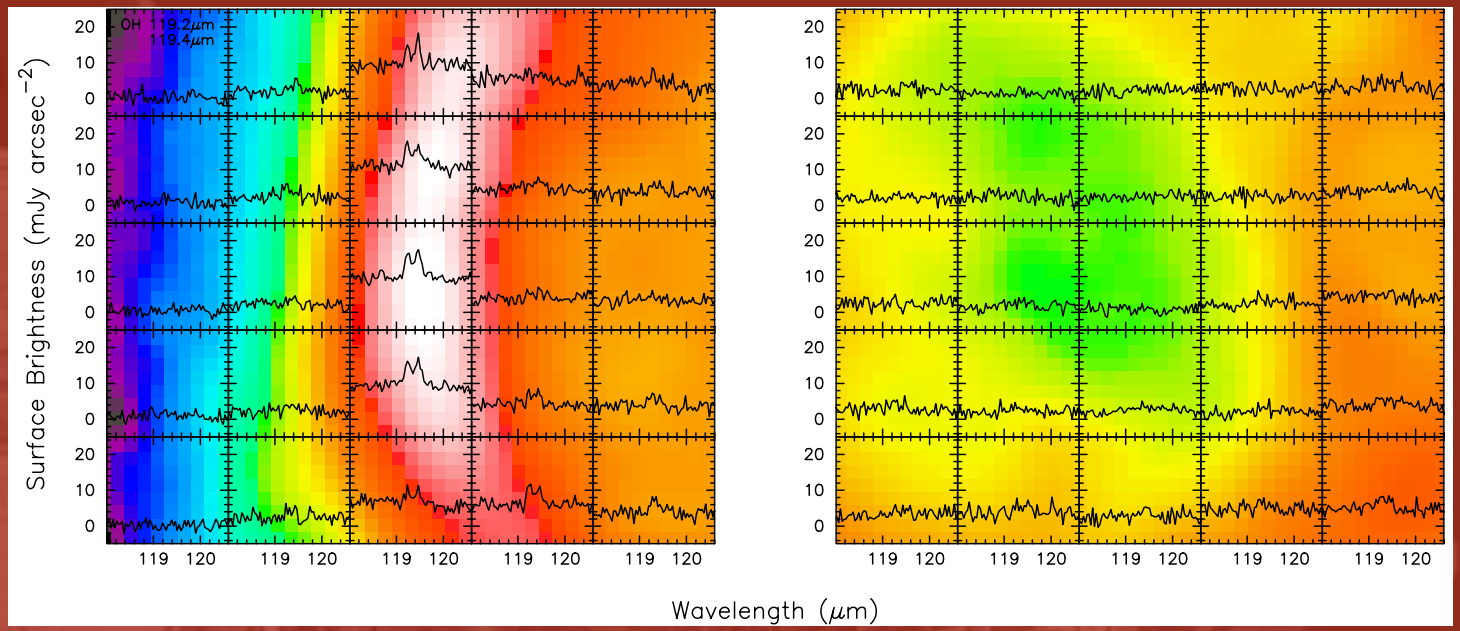




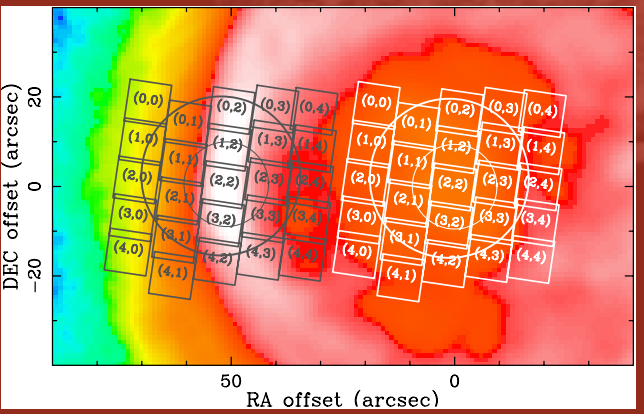
Molecular Line Variations

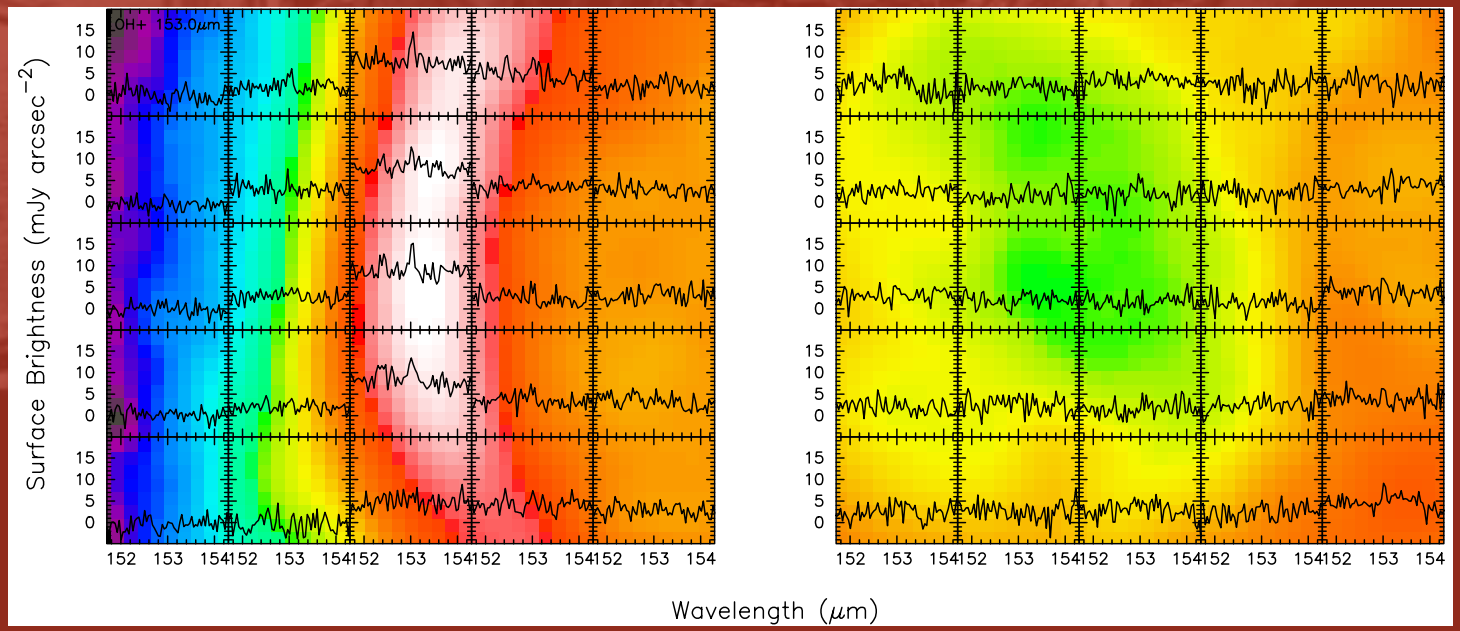
OH 119.2/119.4μm



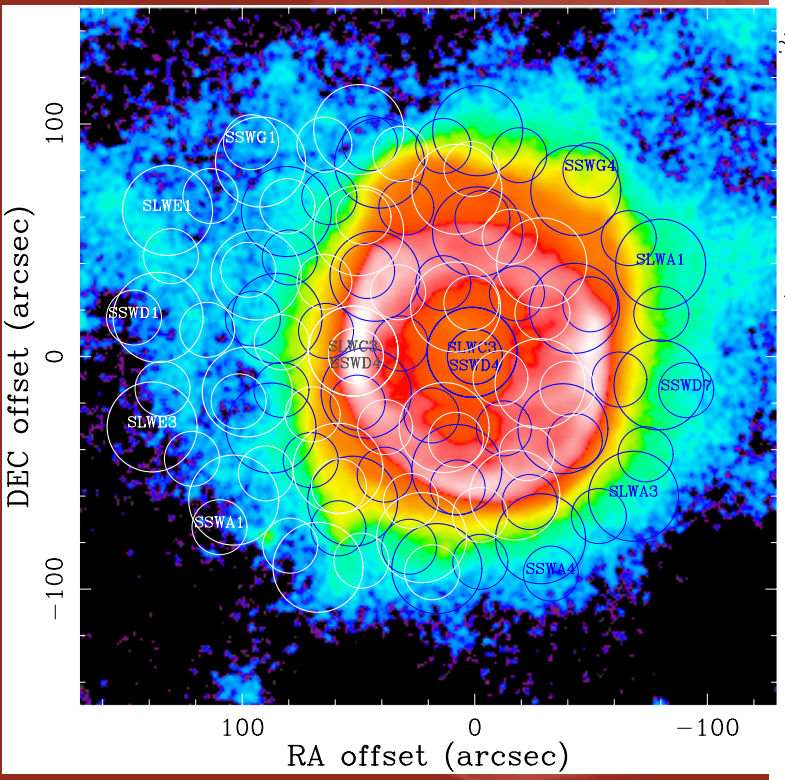


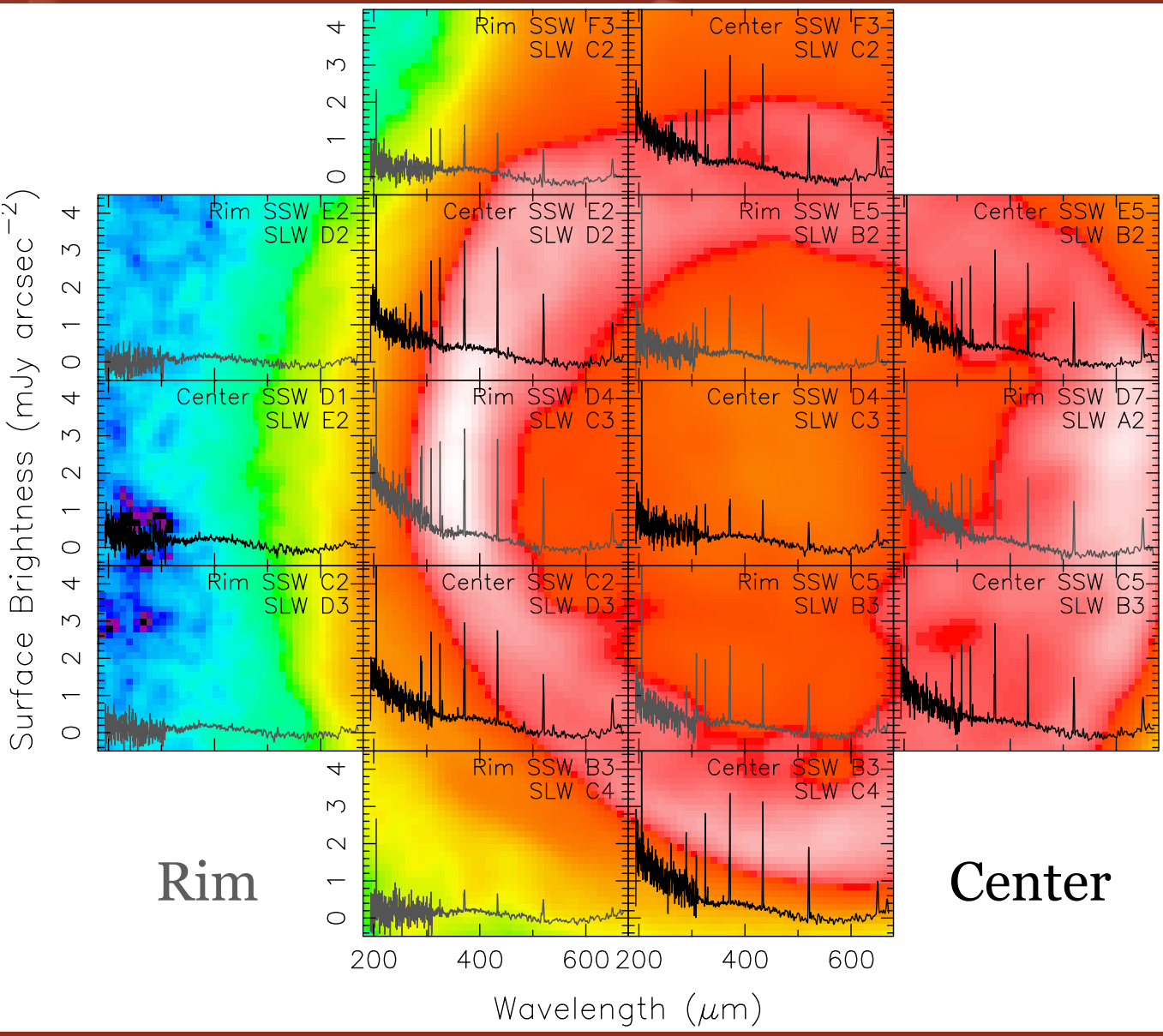
OH+ 152.9μm



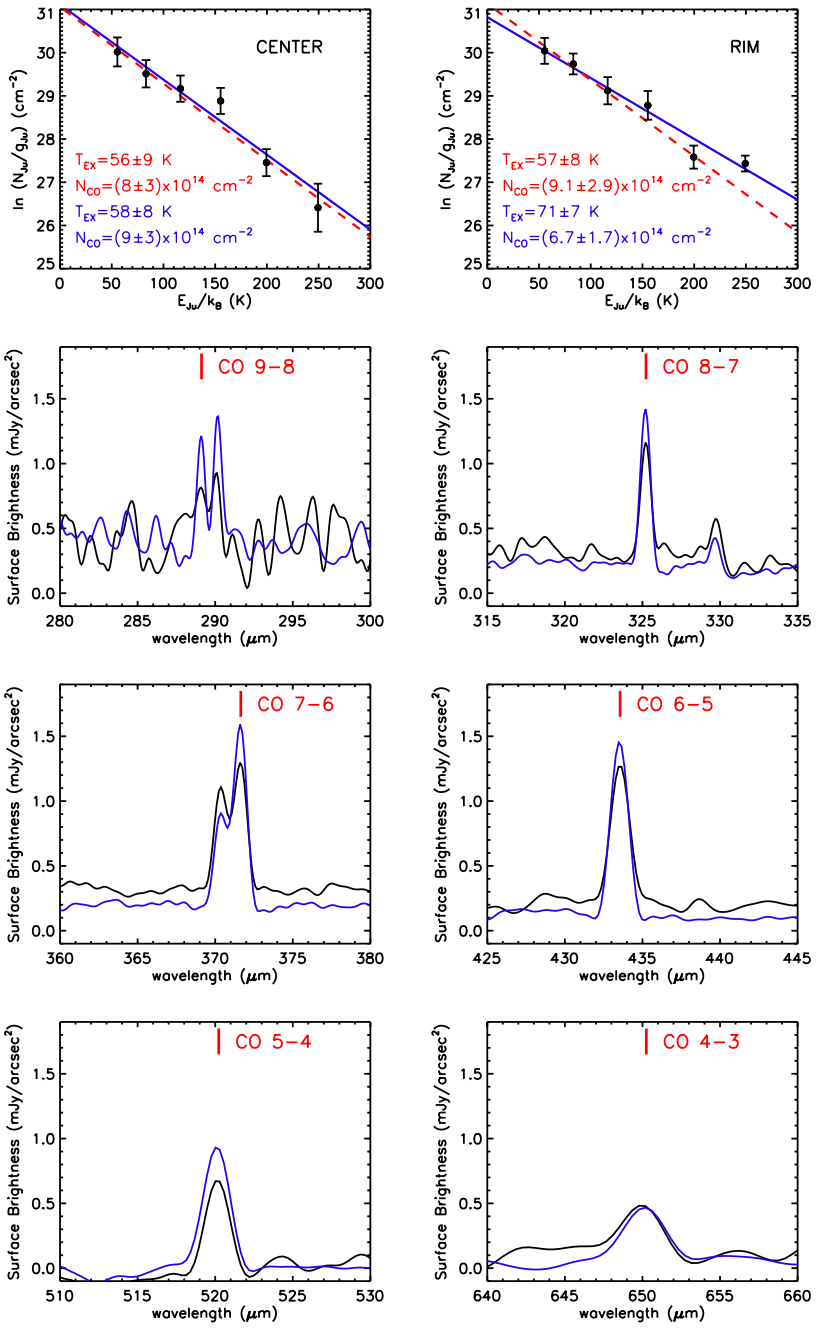


High-J CO transitions





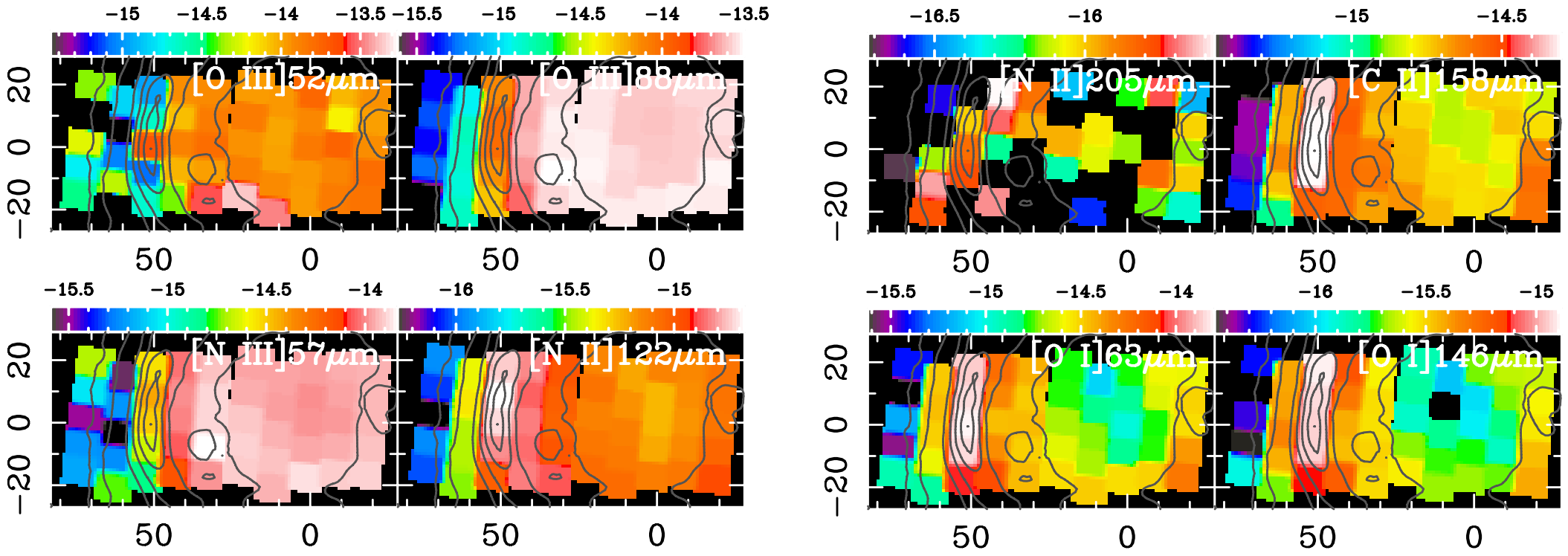
CO Rotation Analysis



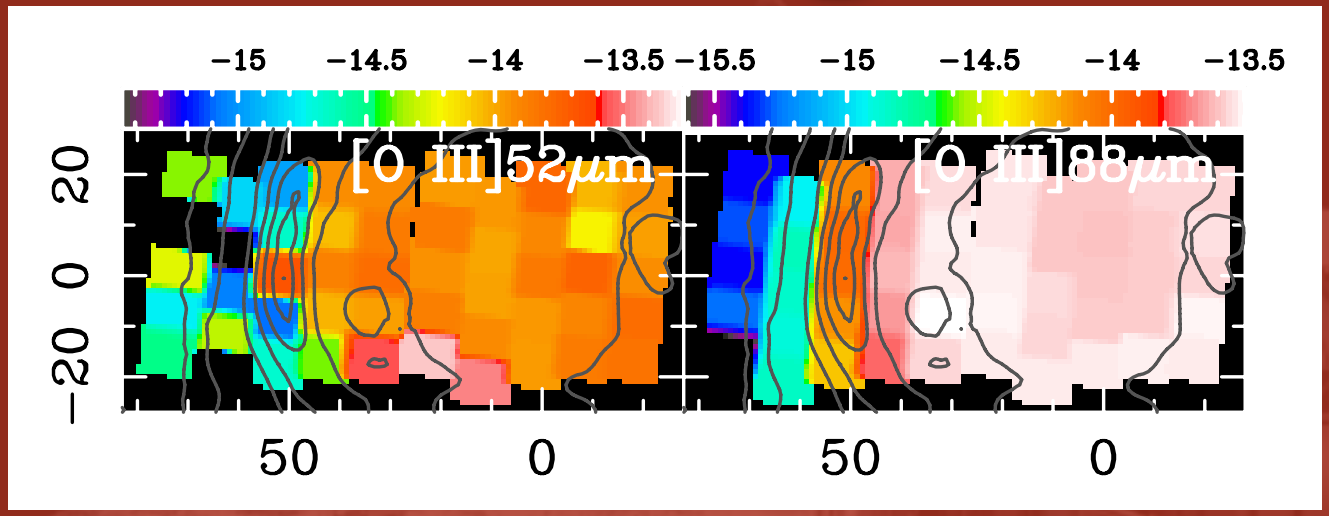
T_{ex} ~ 60 - 70 K

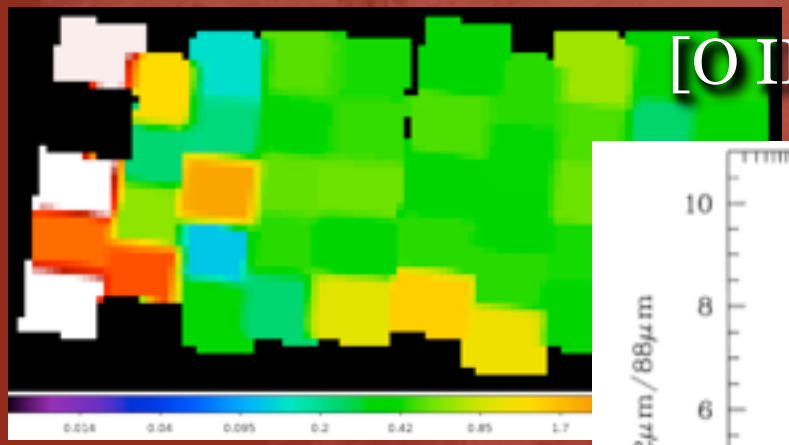
Gas & dust components do not seem to be thermalized (or spatially distinct regions are probed)

Fine-Structure Line Maps

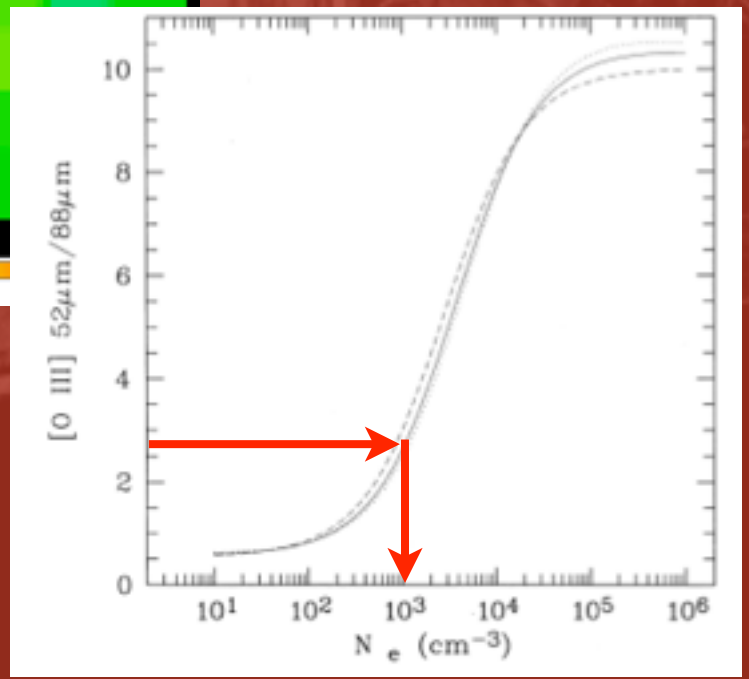


Line Diagnostics: (n_e, T_e)

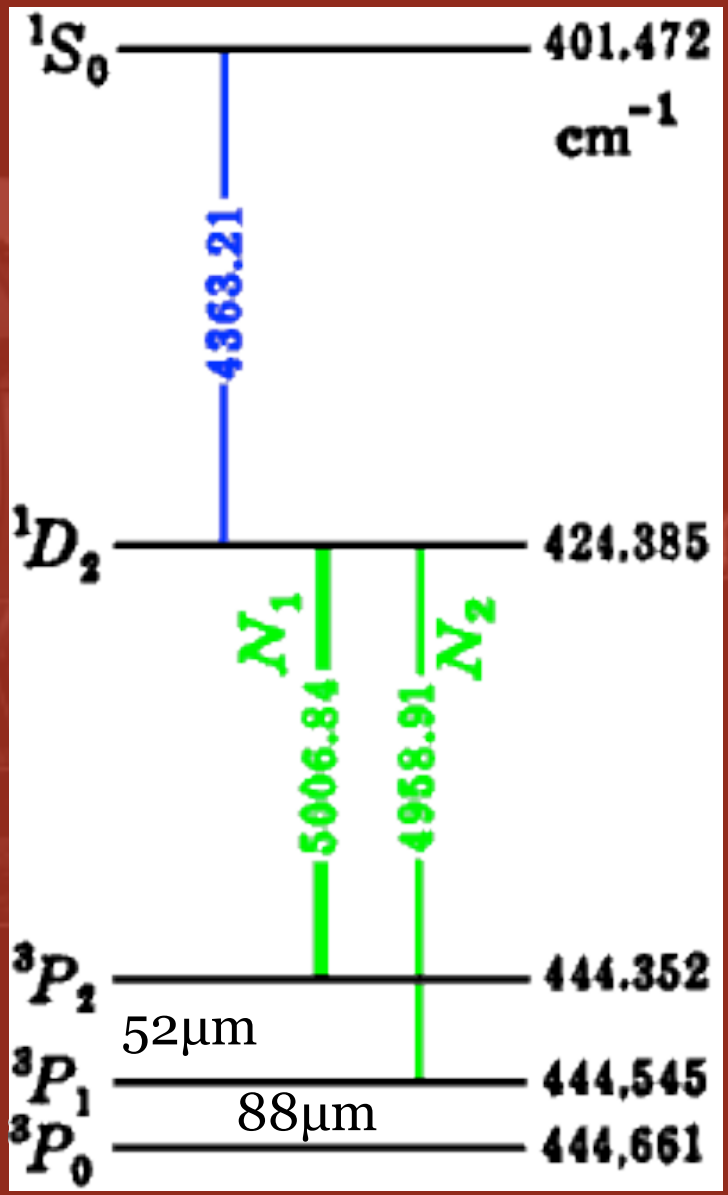




[O III] 52/88 μm ratio

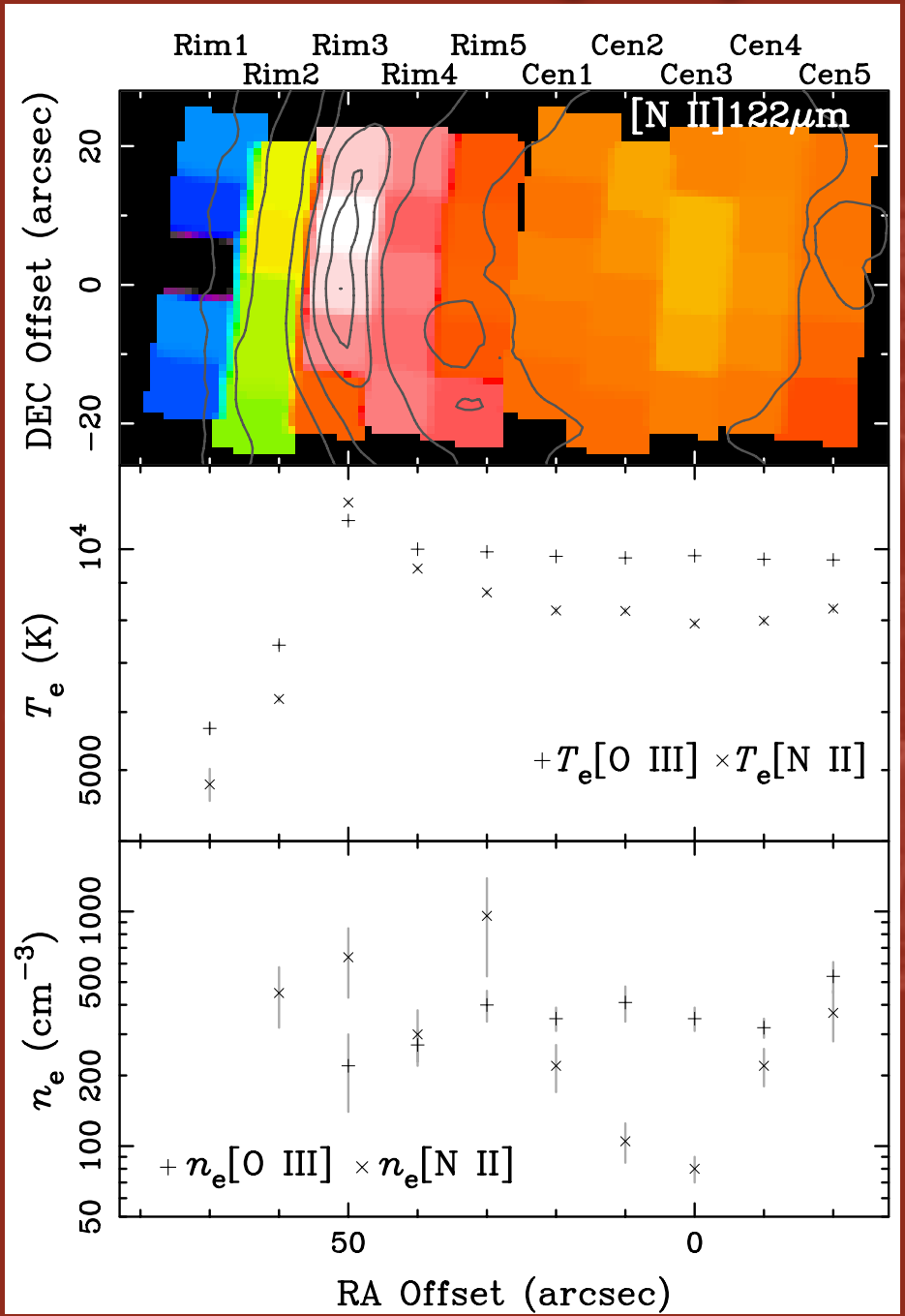


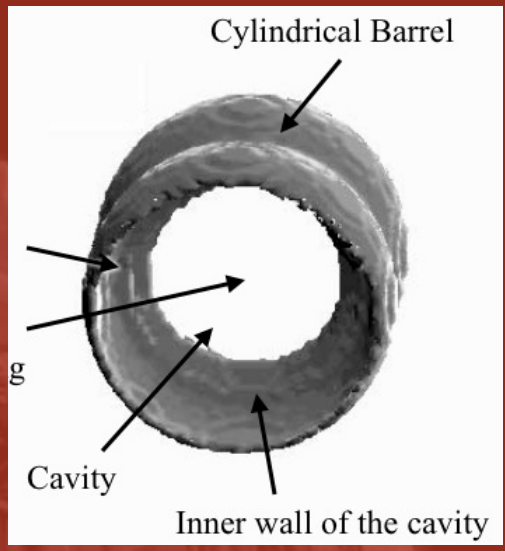
Liu+ (2001)



T_e[O III]λ5007/88μm

(n_e, T_e) Profiles





T_e ~ 10,000 K in the cavity

T_e ~ 10,500 K at the rim peak

T_e[N II] dips at the center (~8,500 K)

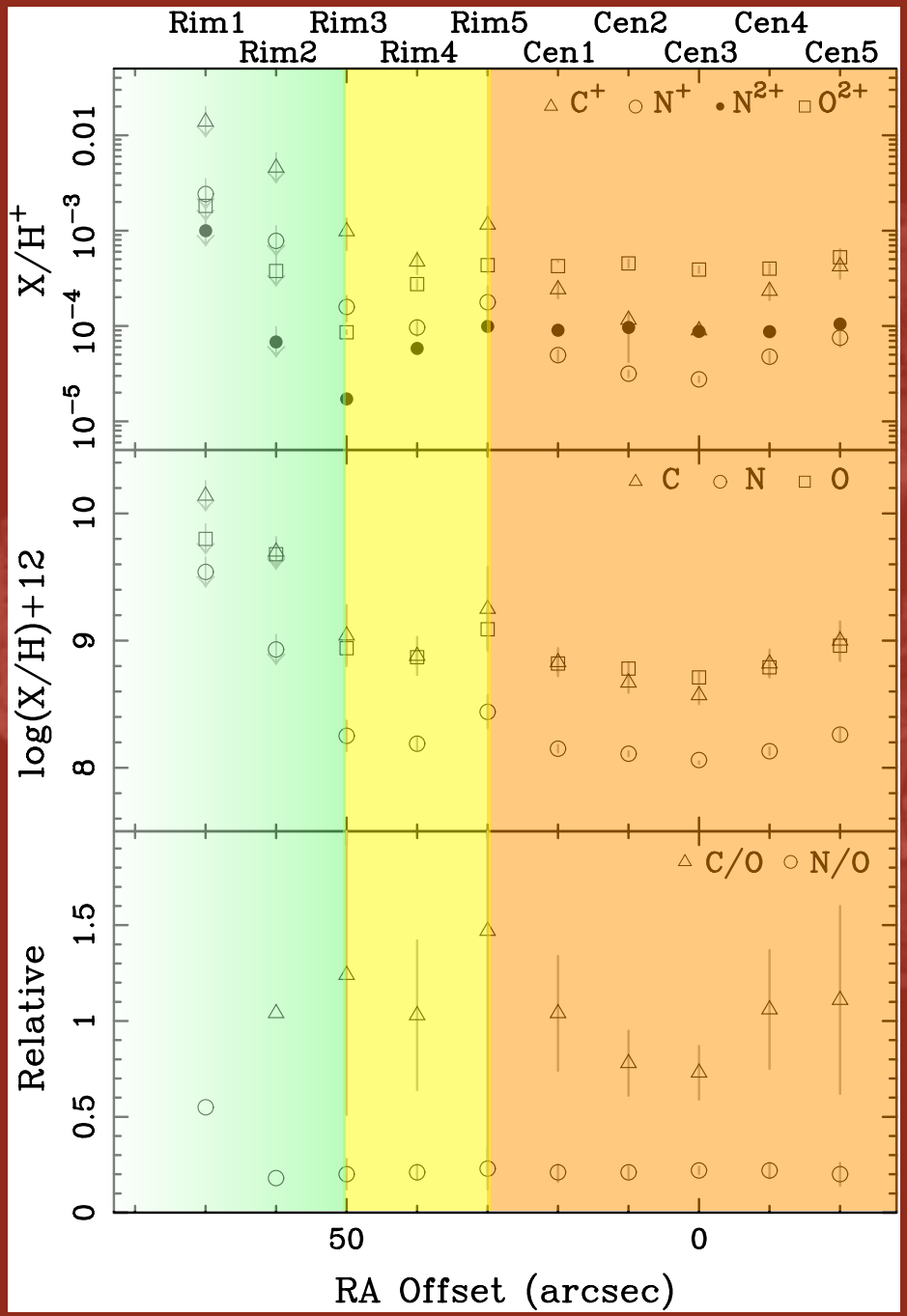
n_e[O III] ~ 400 cm^{-3}

n_e[N II] decreases at the center

n_e[N II] peaks twice

T_e[N II]122/205, n_e[N II]6583/122

Abundance Profiles



Exclusively for the H II region:

$$\frac{N}{H} = \frac{<N^+> + <N^{2+}>}{<H^+>} = \frac{F_{[N\,II]122}/\epsilon_{[N\,II]122} + F_{[N\,III]57}/\epsilon_{[N\,III]57}}{F_{H\beta}/\epsilon_{H\beta}}$$

$$\frac{N}{O} = \frac{<N^{2+}>}{<O^{2+}>} = \frac{F_{[N\,III]57}/\epsilon_{[N\,III]57}}{F_{[O\,III]88}/\epsilon_{[O\,III]88}}$$

$$\frac{C}{N} = \frac{<C^+>}{<N^+>} = \frac{F^{H\,II}_{[C\,II]158}/\epsilon_{[C\,II]158}}{F_{[N\,II]122}/\epsilon_{[N\,II]122}}$$

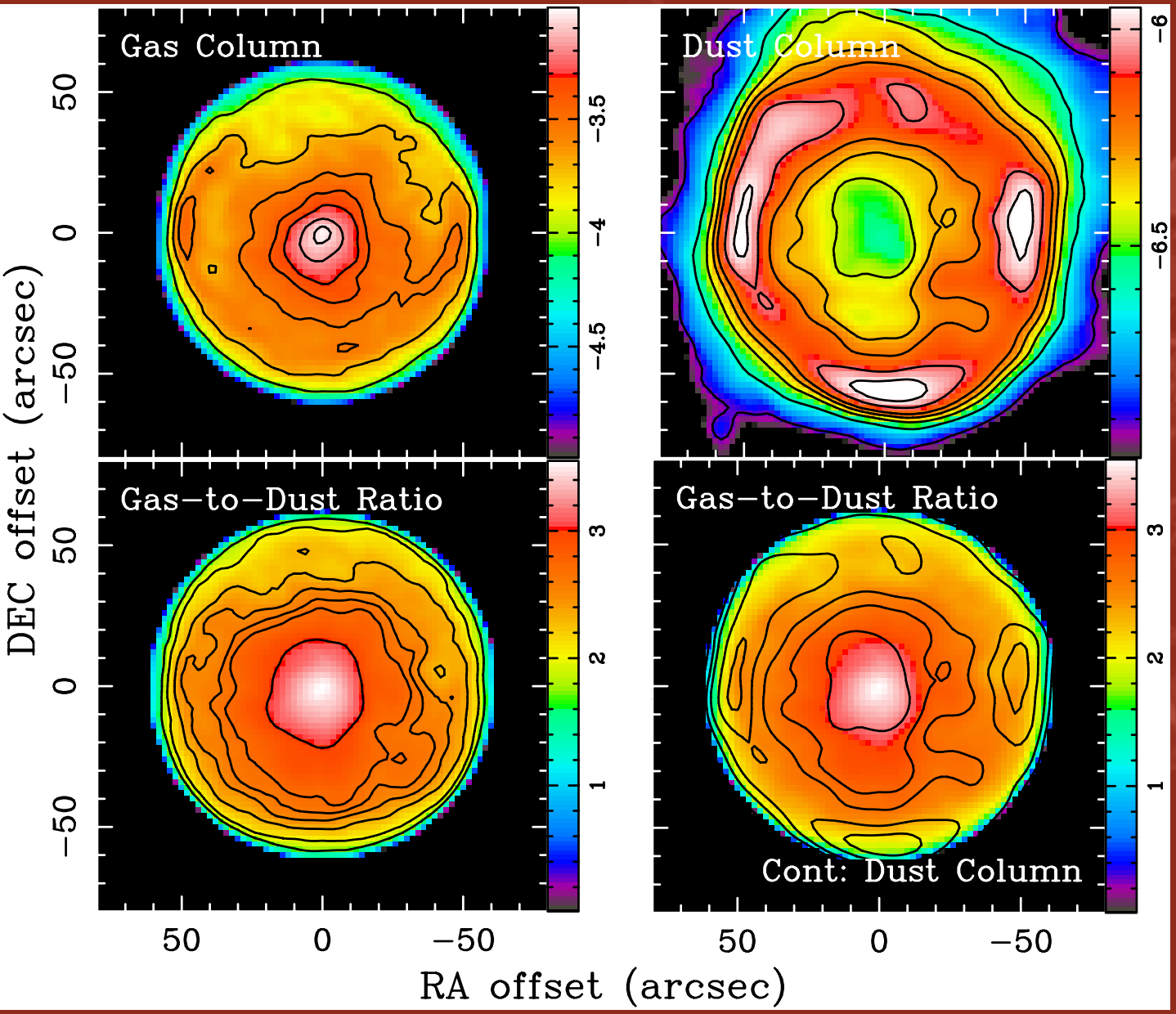
Ionization stratification
(by relative ionic abundance)

O^+ 35.12 eV
N^+ 29.60 eV
He^+ 24.59 eV

C^+ 24.38 eV
N^o 14.53 eV

O^o 13.62 eV
H^+ 13.60 eV
C^o 11.26 eV

Gas-to-Dust Mass Ratio Map



Gas Column:

H_α map compared with H_α emissivity using (T_e, n_e)

$\Rightarrow M_{\text{ionized gas}}$

$M_{\text{ionized gas}}$

$M_{\text{atomic gas}}$

$M_{\text{molecular gas}}$

$\Rightarrow M_{\text{gas}} = 0.86\ M_\odot$

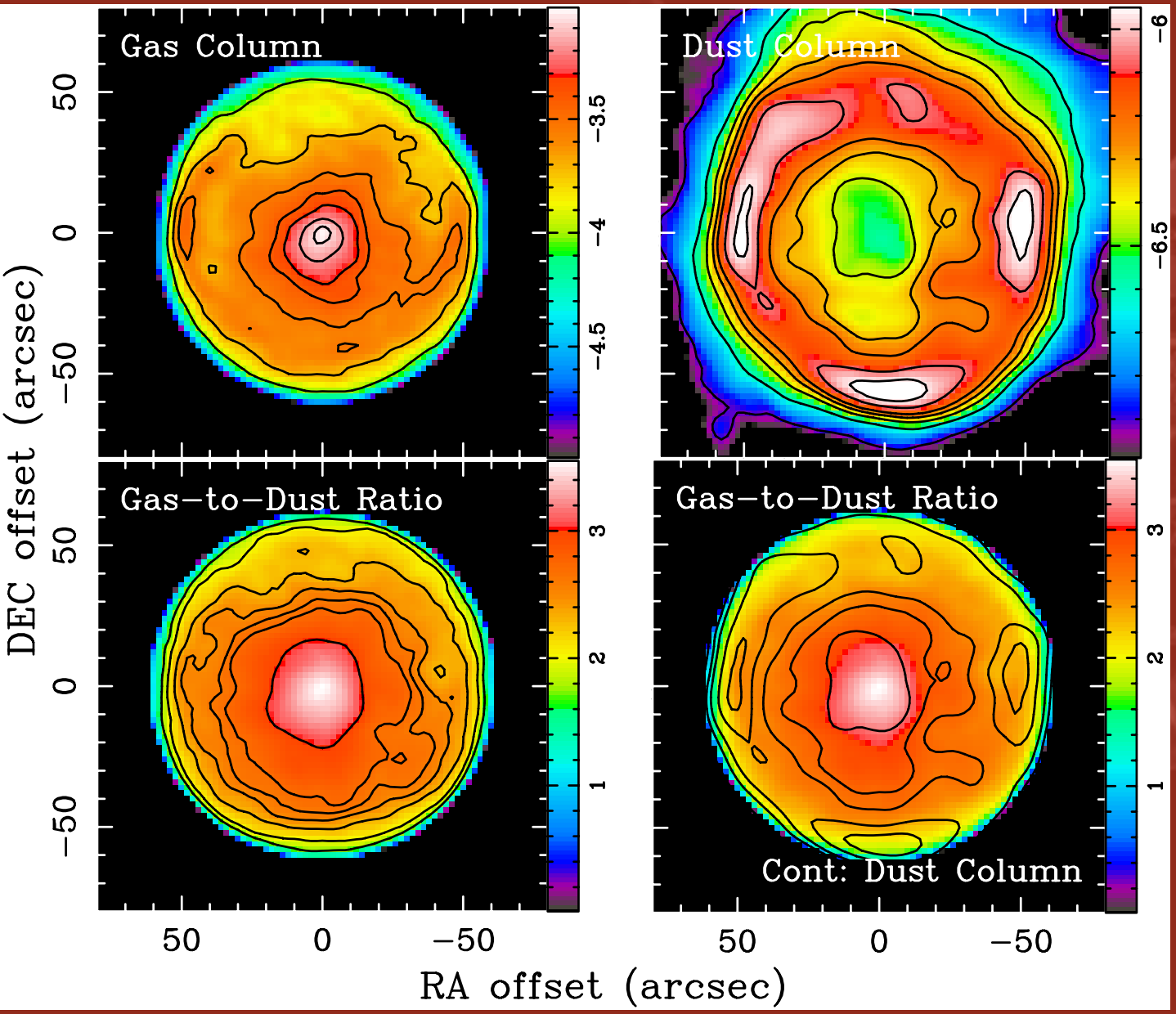
Dust Column:

5-band fitting with a modified BB

$\Rightarrow T_{\text{dust}}, \beta, \tau$

$\Rightarrow M_{\text{dust}} = 0.004\ M_\odot$

Gas-to-Dust Mass Ratio Map



Gas Column:

$M_{\text{ionized gas}}$

$M_{\text{atomic gas}}$

$M_{\text{molecular gas}}$

$\Rightarrow M_{\text{gas}} = 0.86\ M_{\odot}$

Dust Column:

5-band fitting with a modified BB

$\Rightarrow T_{\text{dust}}, \beta, \tau$

$\Rightarrow M_{\text{dust}} = 0.004\ M_{\odot}$

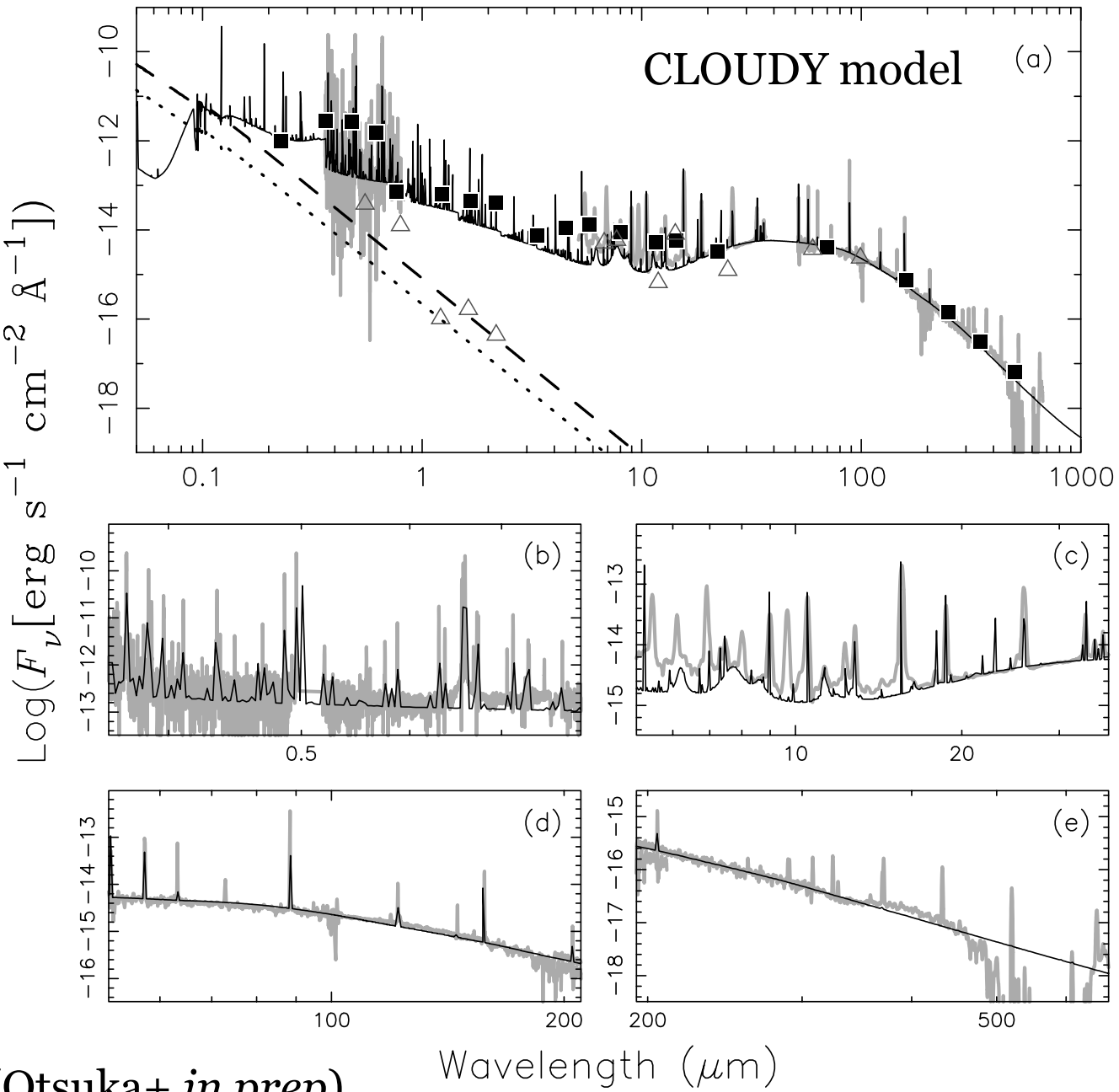
Gas-to-Dust Ratio:

500-50 radially decreasing in barrel

median: 270±141

~400 C-rich (Knapp 1985)

Photo-Ionization Model



(Otsuka+ *in prep*)

Fit with data
from UV to Far-IR
(most comprehensive
ever done so far)

Optical lines/Ionized gas
Far-IR lines/Neutral gas
0.55 $M_\odot$
Far-IR cont/Dust Grains
0.014 $M_\odot$?

CO lines/Molecular Gas
0.2 $M_\odot$

Gas/Dust Ratio 54?

WD core 0.6 $M_\odot$

M_* 1.364 $M_\odot$

Summary

- HerPlaNS data products are (almost) ready
- For NGC 6781, (Aleman+ *submitted*)
  - Detected OH^+ in 3 PNs (with MESS 5 PNs total)
  - Broadband maps of thermal dust emission yielded T_{dust}, β, optical depth maps, and then, an empirical M_{dust} map (0.004 $M_\odot$ total)
  - Forbidden line maps of gas emission yielded (T_e, n_e) maps, and then, an empirical M_{gas} map (0.8 $M_\odot$ total) and abundance maps (ionization stratification seen)
  - An empirical gas-to-dust mass ratio map shows values of 500-50 over the dust shell (with the median of 270 ± 141). (Ueta+ *submitted*)

Current Status

- Far-IR continua probe the dust component (Ladjal+ *in prep*)

  $T_{\rm dust}$, $M_{\rm dust}$ profiles, optically thin structure probe

- Far-IR lines probe the ionized, neutral, and molecular gas component (Exter+ *in prep*; Rattray+ *in prep*)

  ($T_{\rm e}$, $n_{\rm e}$) profiles, abundance profiles (H II region/PDR)

  First time in the far-IR. Optical follow-up (GemPlaNS).

- Most comprehensively constrained (from UV to Far-IR) photo-ionization models (Otsuka+ *in prep*)

  Empirical Gas-to-Dust mass ratio - not a single value!

- We will do this for all 11 survey samples + archival

More to Do

- SPIRE data need to be corrected for the residual background/instrumental effects (calibration of outer bolometers)
- Radial (T_e, n_e) tested $\Rightarrow$ 2-D (T_e, n_e) will be made
- Do the analyses for other sources in the sample
- Other analyses:
  - line ID
  - $^{12}C/^{13}C$ ratio,
  - X/Far-IR connection (OH+ due to soft X-rays?)
  - CLOUDY/MOCASSIN models

References

Aleman, I., et al. 2014, A&A, submitted
Chu, Y.-H., et al. 2001, Chandra X-ray Observatory Center, CXC PR 01-01
Herwig, F. 2005, ARA&A, 43, 435
Kastner, J. H., et al. 2003, ApJ, 591, L37
Knapp, G. R. 1985, ApJ, 293, 273
Latter, W. B., et al. 2000, ApJ, 539, 783
Liu, X.-W., et al. 2001, MNRAS, 323, 343
Mauron, N., Huggins, P. J. 1999, A&A, 349, 203
Meixner, M., et al. 1999, ApJS, 122, 221
PACS Consortium 2013, PACS User's Manual, HERSCHEL-DOC-0832, Version 2.5.1
Schwarz, H. E., & Monteiro, H. 2006, ApJ, 648, 430
Ueta, T., Meixner, M., & Bobrowsky, M. 2000, ApJ, 528, 861
Ueta, T., et al. 2014, A&A, submitted
Valtchanov, I. 2011, SPIRE User's Manual, HERSCHEL-DOC-0798, version 2.4