Carbon in low Metallicity PDRs

Markus Röllig[1]

V. Ossenkopf[1,3], J. Stutzki[1], A. Sternberg[4], C. Kramer[1],
M.Cubick[1], H. Jakob[1], B. Mookerjea[2], R. Simon[1], F. Bensch[5],

[1]KOSMA, Universität zu Köln
[2]University of Maryland, USA
[3]SRON, Groningen, Netherlands
[4]Tel Aviv University, Israel
[5]Radioastronomisches Institut der Universität Bonn

Workshop in Extragalactic and Galactic ISM - Modelling in an ALMA Perspective

Introduction

- PDR – a working definition:
  Photo
  Dissociation
  Region

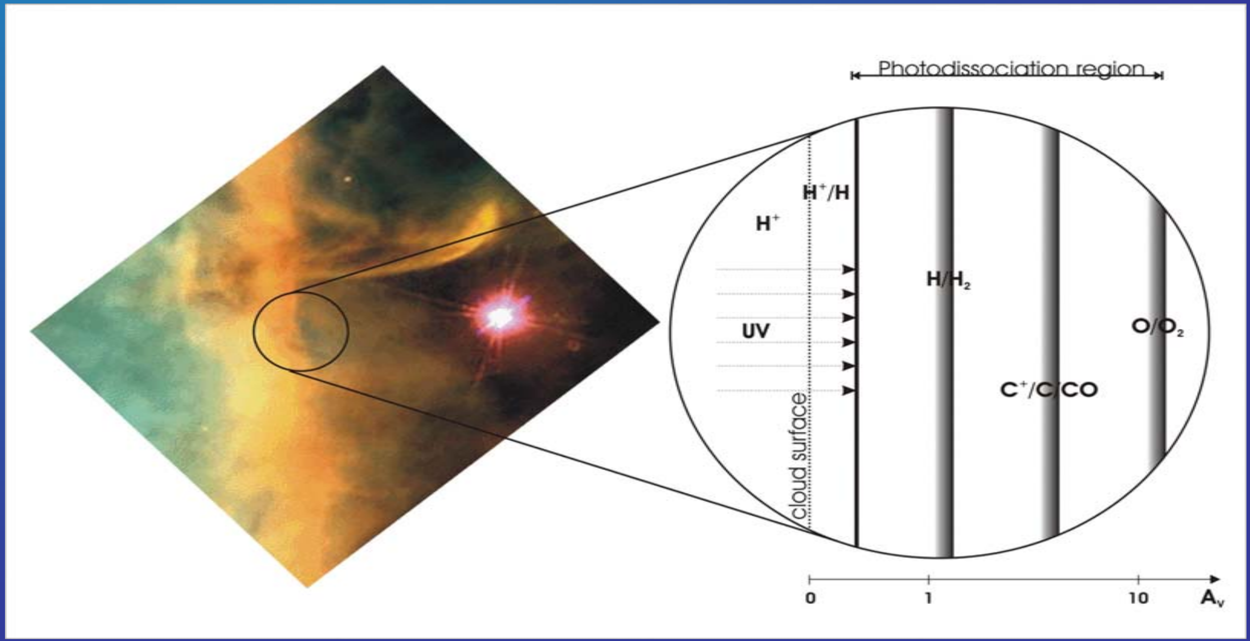
- This implies the existence of atomic and molecular gas PLUS the dissociating photons

- Also used:
  Photon Dominated Region

- But much broader classification (HII regions, PNe, ...)

Introduction

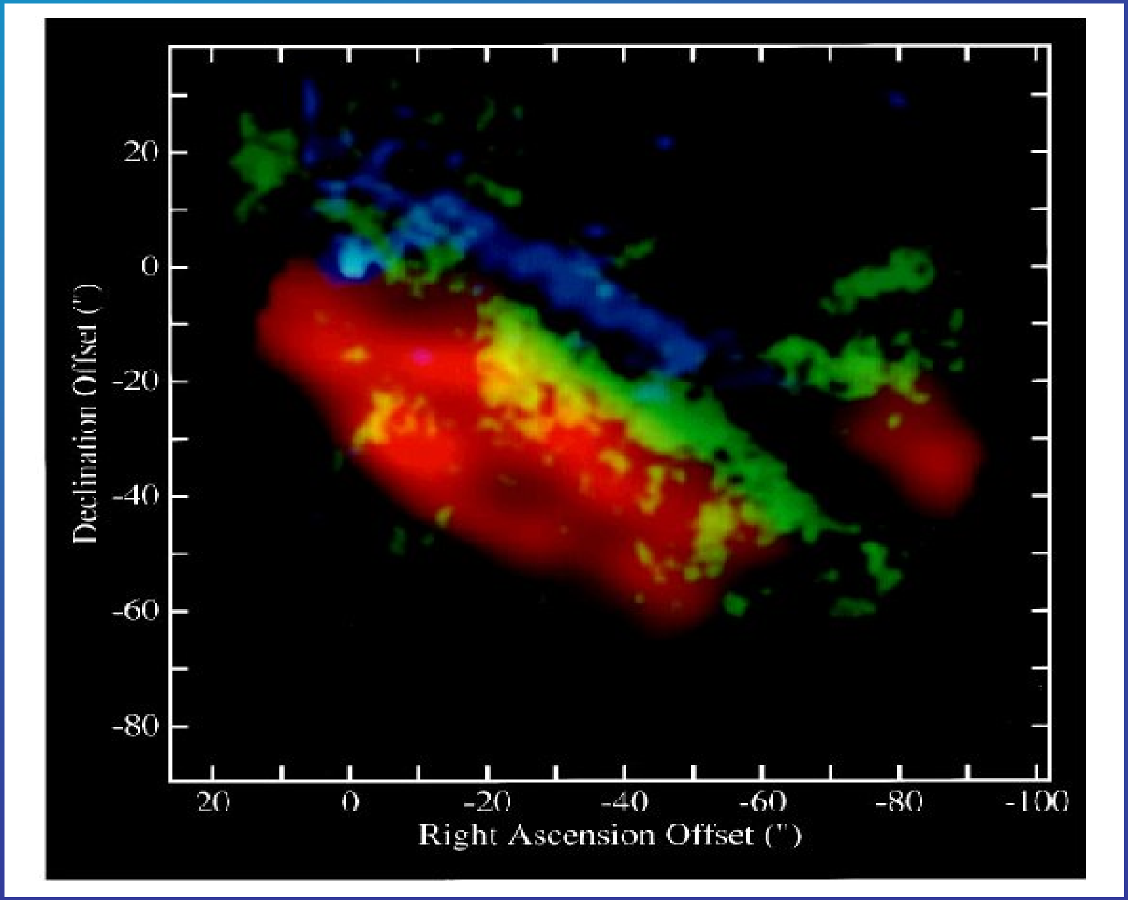
- PDRs occur where far-ultraviolet (FUV) radiation (6-13.6 eV) dominates the physics (e.g. heating and cooling) and determines the chemical composition of the gas.



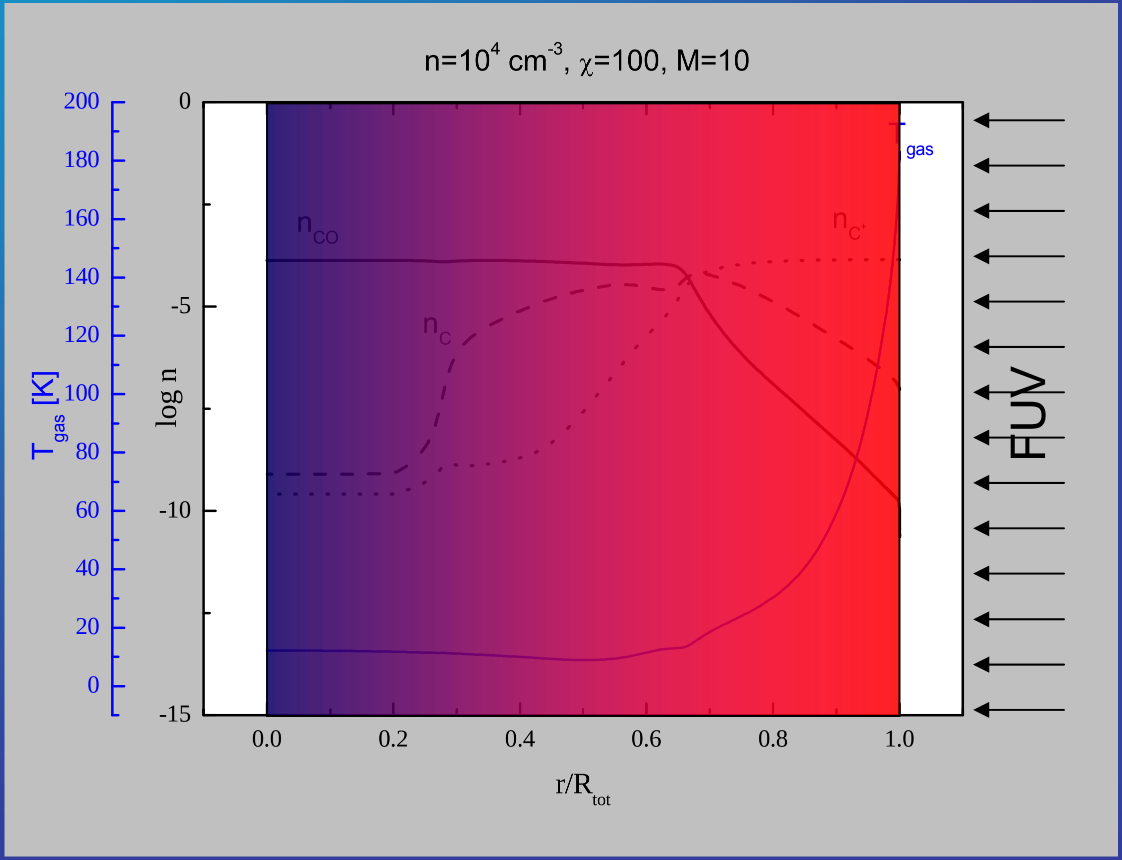
- •Introduction
- •The KOSMA-τ Code
- •Low Z PDRs
- •[CII]/CO(1-0)
- •[CI]/CO(1-0)
- •Clumpy PDRs
- •Modeling the MW
- •Summary

Introduction

typical stratification: C^+/C/CO, H/H_2, S^+,S,SO,…

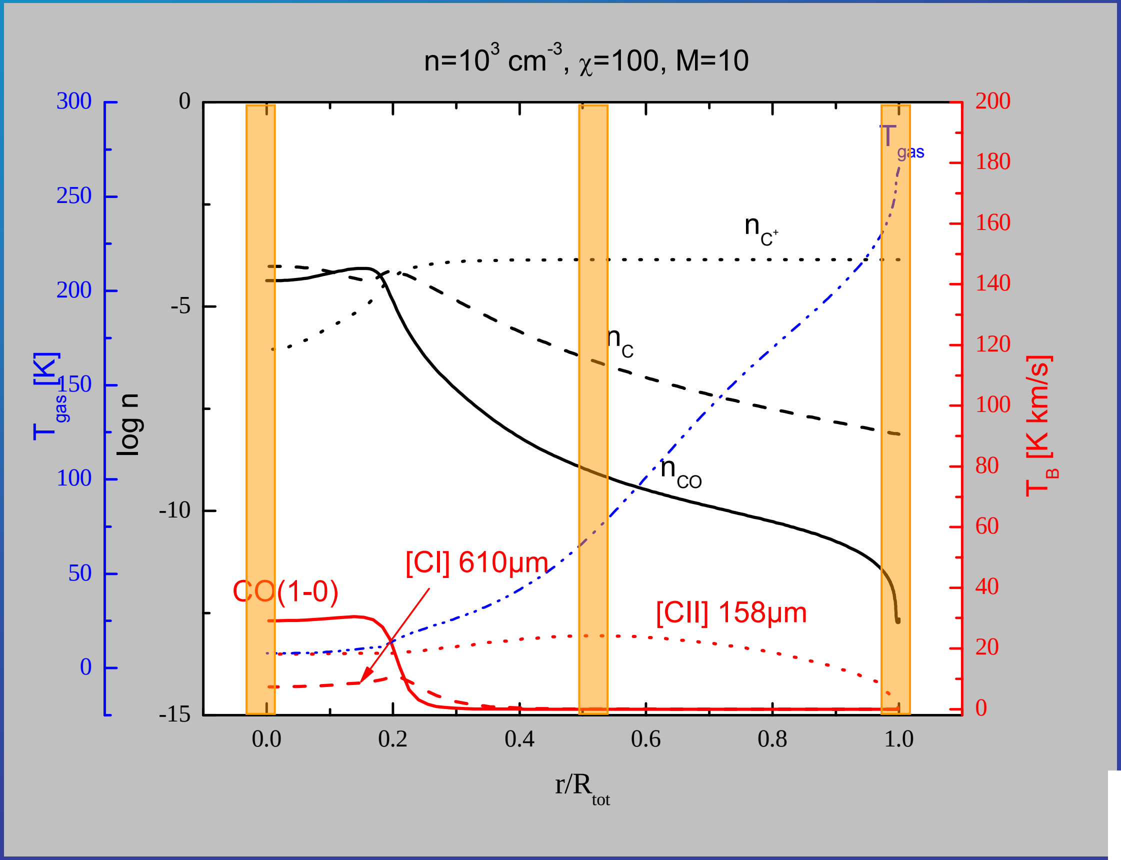


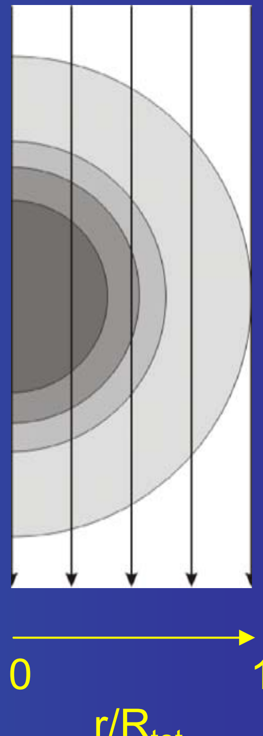
Introduction

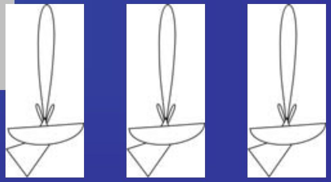


The KOSMA-τ Code

- •Introduction
- •The KOSMA-τ Code
- •Low Z PDRs
- •[CII]/CO(1-0)
- •[CI]/CO(1-0)
- •Clumpy PDRs
- •Modeling the MW
- •Summary

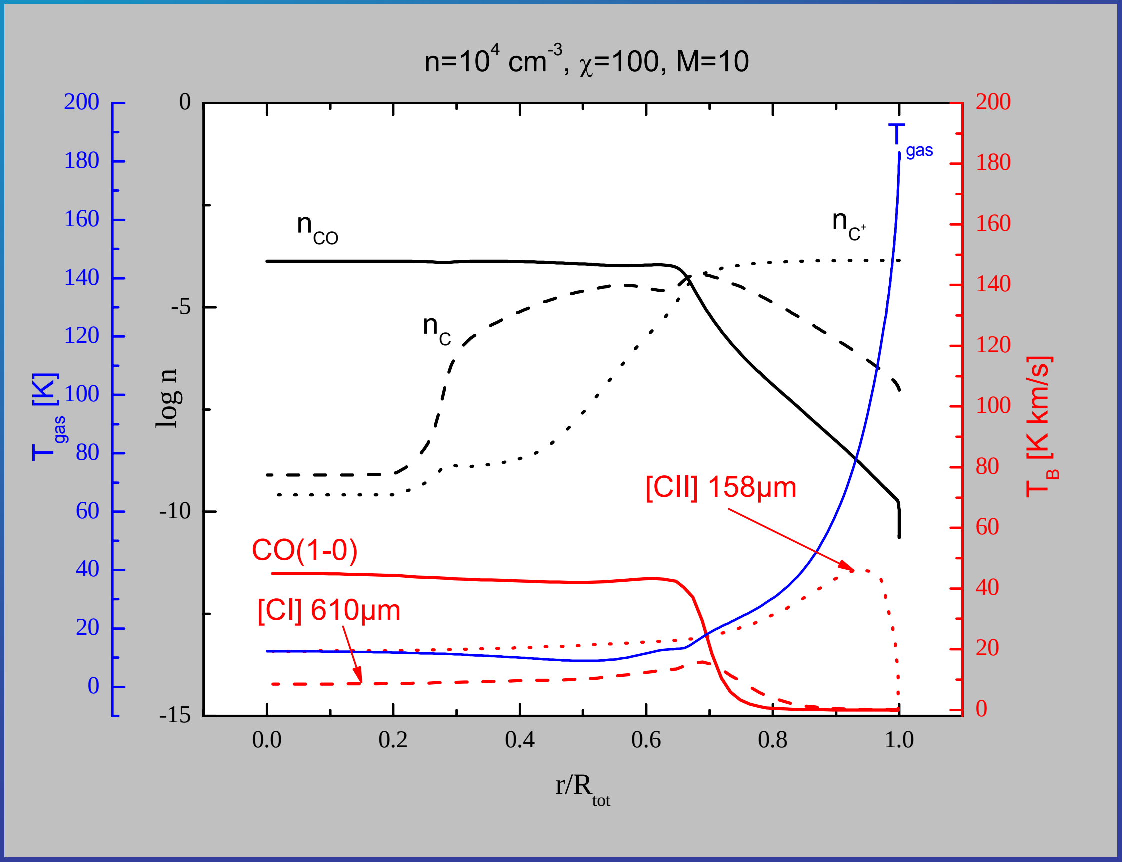


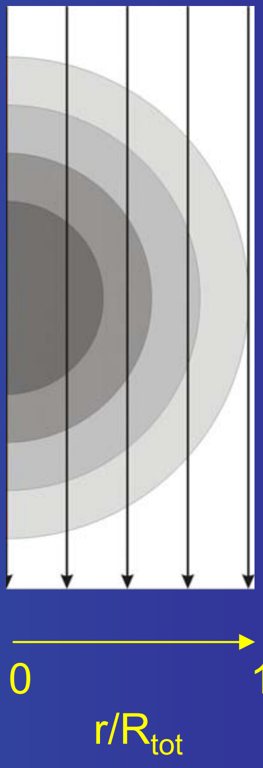




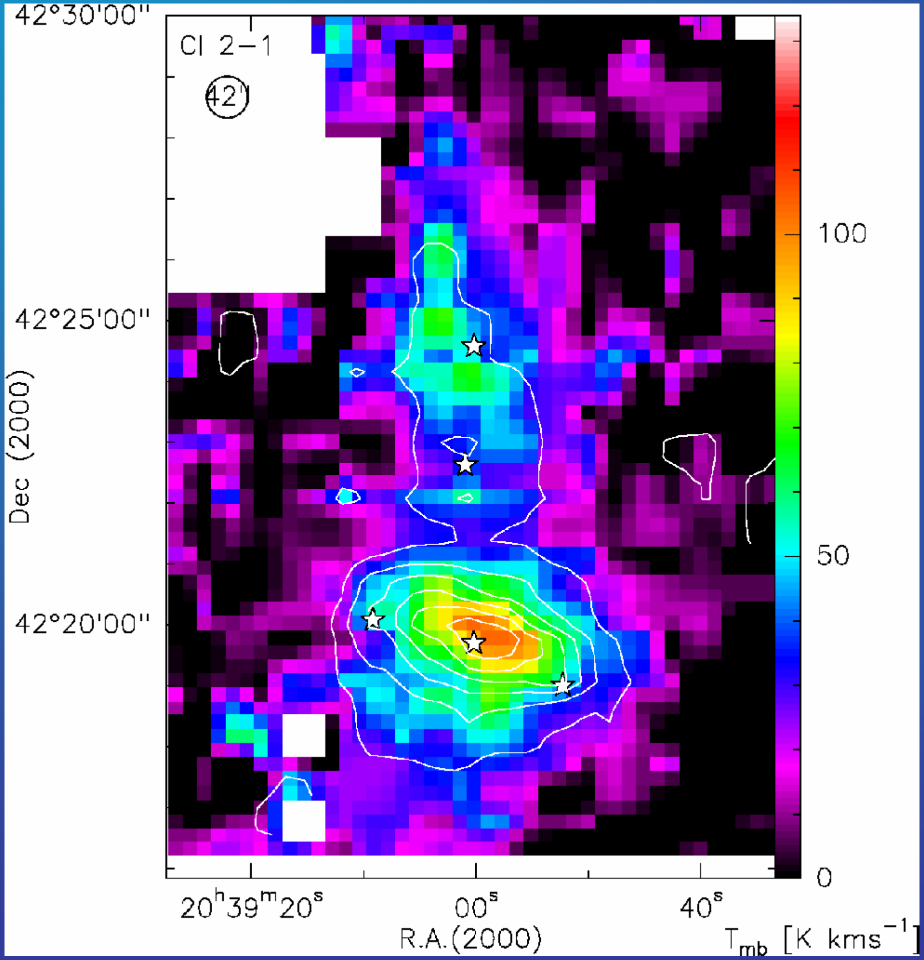
- •Introduction
- •The KOSMA-τ Code
- •Low Z PDRs
- •[CII]/CO(1-0)
- •[CI]/CO(1-0)
- •Clumpy PDRs
- •Modeling the MW
- •Summary

The KOSMA-τ Code





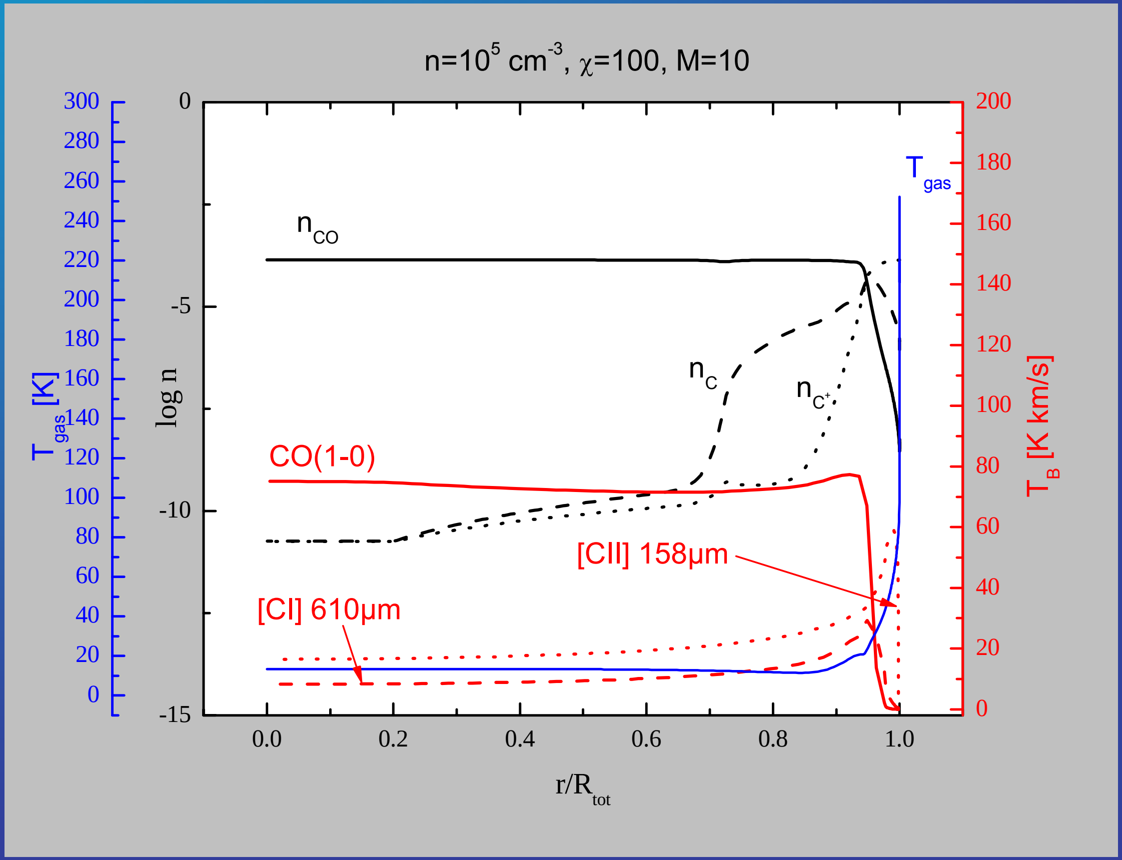
The KOSMA-τ Code

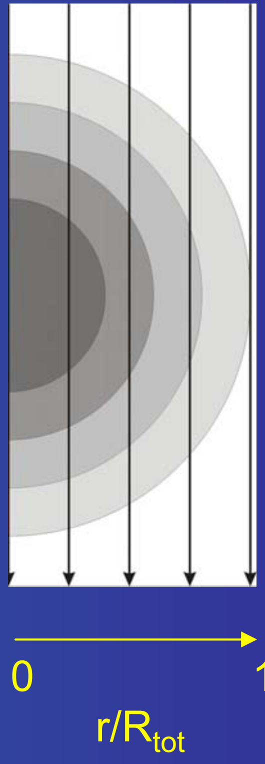


DR21 in Cygnus X: CO 7-6 & [CI] $^3P_2$-$^3P_1$

Figure:
3m-KOSMA maps of [CI] 2-1 (color) and CO 7-6 (contours) at 42" HPBW (0.35 pc)
(Jakob et al. 2005 in prep.)

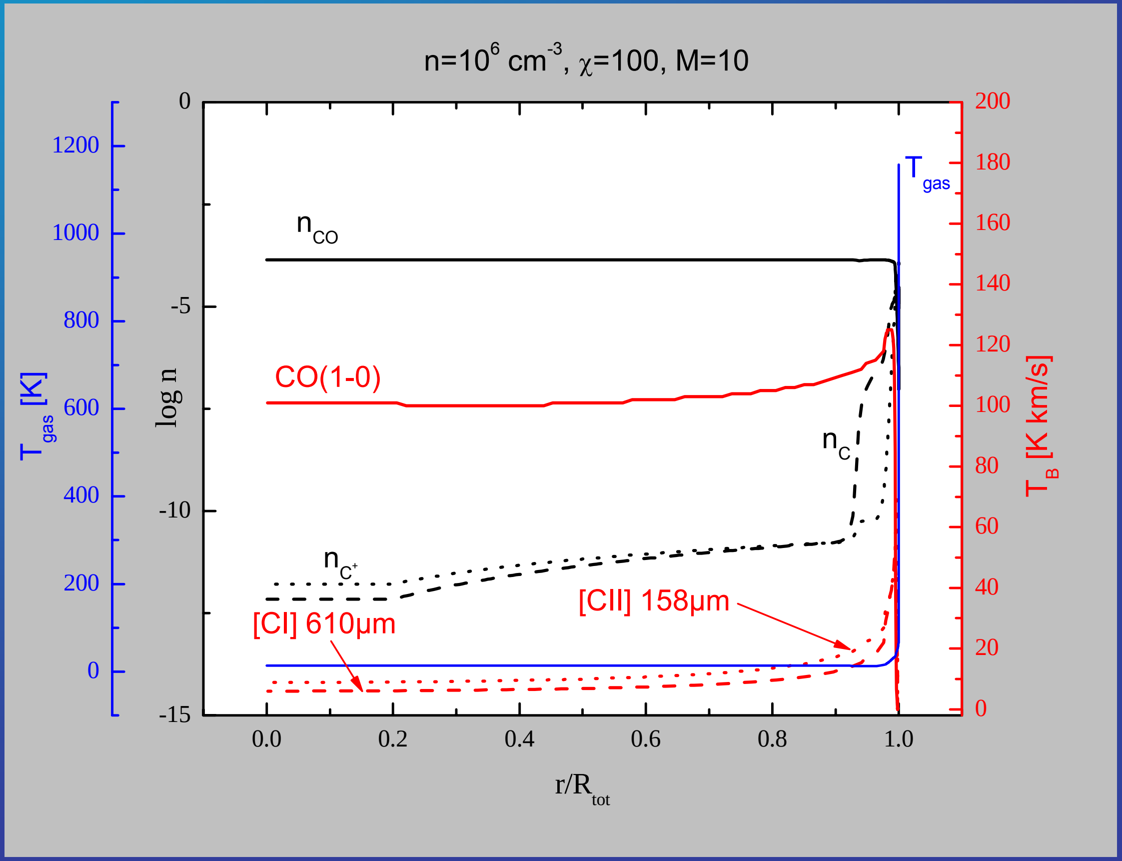
The KOSMA-τ Code

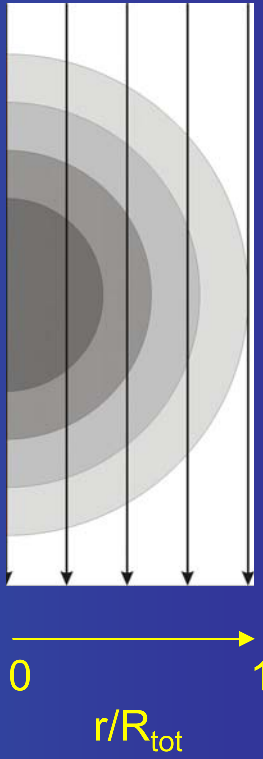




The KOSMA-τ Code

- •Introduction
- •The KOSMA-τ Code
- •Low Z PDRs
- •[CII]/CO(1-0)
- •[CI]/CO(1-0)
- •Clumpy PDRs
- •Modeling the MW
- •Summary





•Introduction

•The KOSMA-τ Code

•Low Z PDRs

•[CII]/CO(1-0)

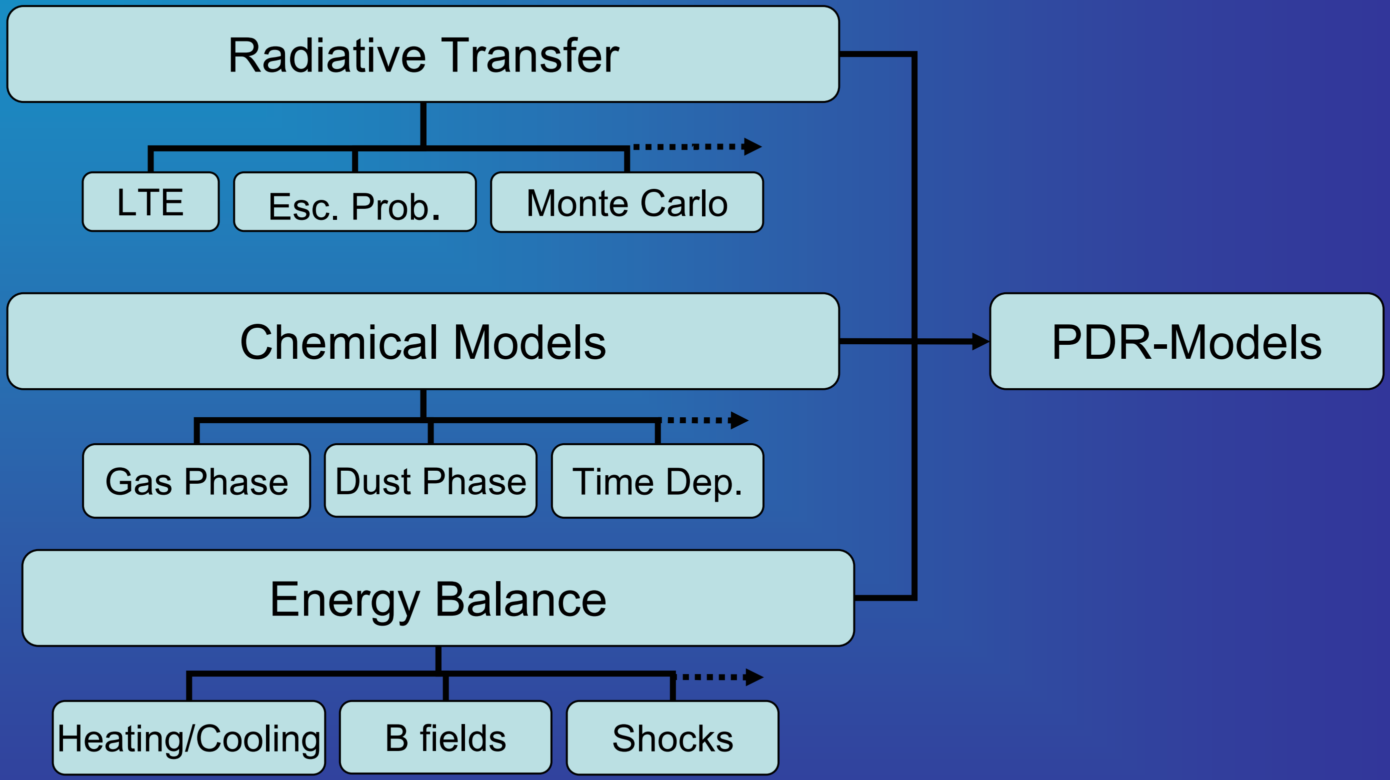
•[CI]/CO(1-0)

•Clumpy PDRs

•Modeling the MW

•Summary

Introduction



The KOSMA-τ Code

Model Name	*Authors*
Aikawa	*H.-H. Lee, E. Herbst, G. Pineau des Forets, J. Le Bourlot, Y. Aikawa, N. Kuboi*
KOSMA-τ-2	*H. Störzer, B. Köster, M. Zilinsky, U. Leuenhagen, S.Jeyakumar, F. Bensch*
CLOUDY	*G.J. Ferland, P. van Hoof, N. P. Abel, G. Shaw*
COSTAR	*I. Kamp, F. Bertoldi, G.-J. van Zadelhoff*
HTBKW	*D. Hollenbach, A.G.G.M. Tielens, M.G. Burton, M.J. Kaufman, M.G. Wolfire*
KOSMA-τ-1	*H. Störzer, B. Köster, M. Zilinsky, U. Leuenhagen, S.Jeyakumar, M.Röllig, A.Sternberg*
Lee96mod	*H.-H. Lee, E. Herbst, G. Pineau des Forets, E. Roueff, J. Le Bourlot*
Leiden	*J. Black, E. van Dishoeck, D. Jansen and B. Jonkheid*
Meijerink	*R.Meijerink, M.Spaans*
Meudon	*J. Le Bourlot, E. Roueff, F. Le Petit*
Sternberg	*A.Sternberg, A.Dalgarno*
UCL_PDR	*S. Viti, Wing-Fai Thi, T. Bell*

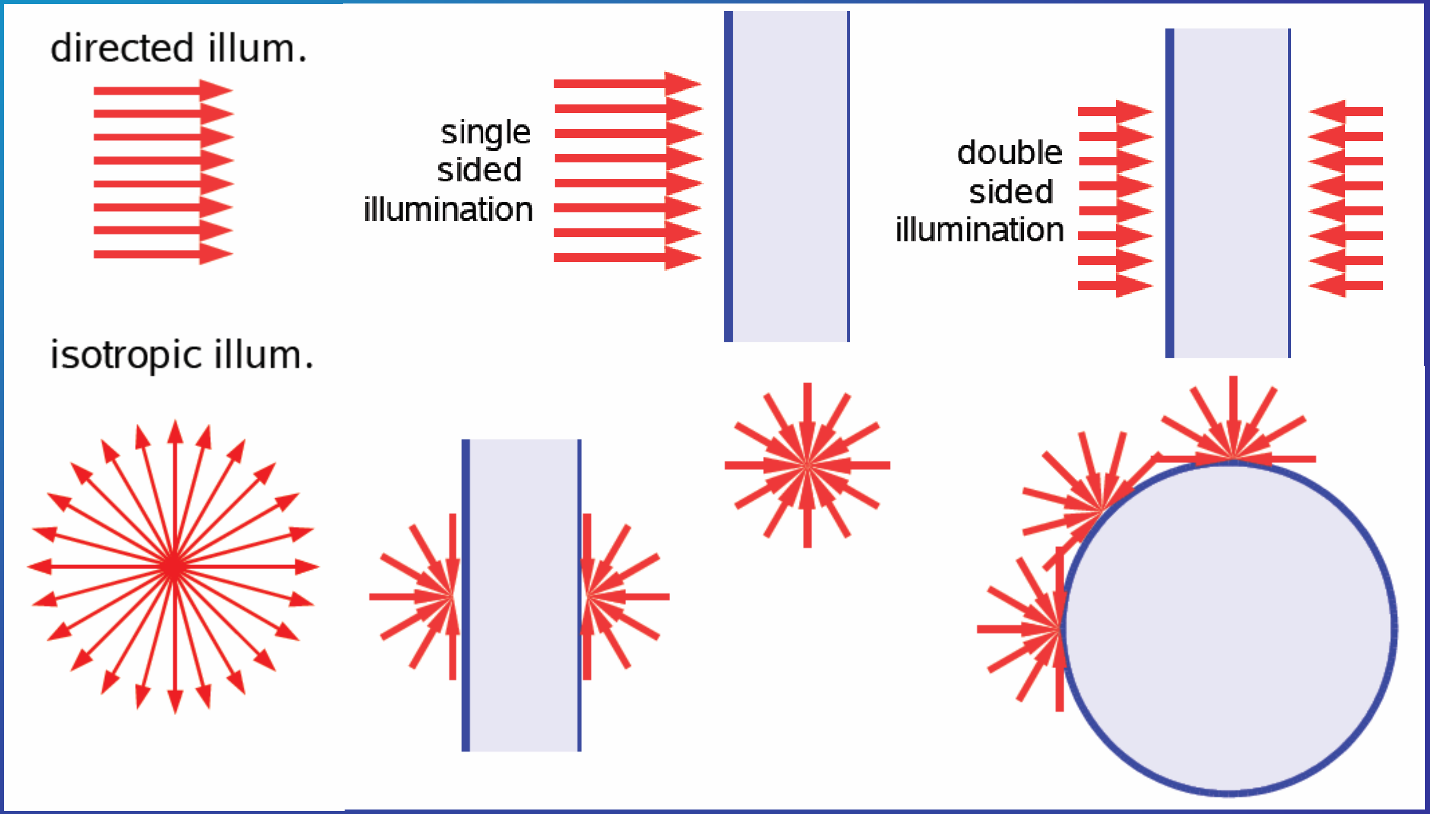
The KOSMA-τ Code

- spherical symmetry
- isotropic FUV field
- density profile (4 parameter) $n(r) = n_0 \cdot \left(\frac{r}{R} \right)^{-\alpha}$
- D/G, Z as free parameter
- 20 heating/cooling processes
- modular, steady-state, gas-phase chemistry (UMIST95/99/...)
- pre-shielding possible
- external multi-shell RT code computes emergent line intensities (CO, ^{13}CO, CI, CII, OI,...)
- clump-mass & mass-size relations applicable

The KOSMA-τ Code

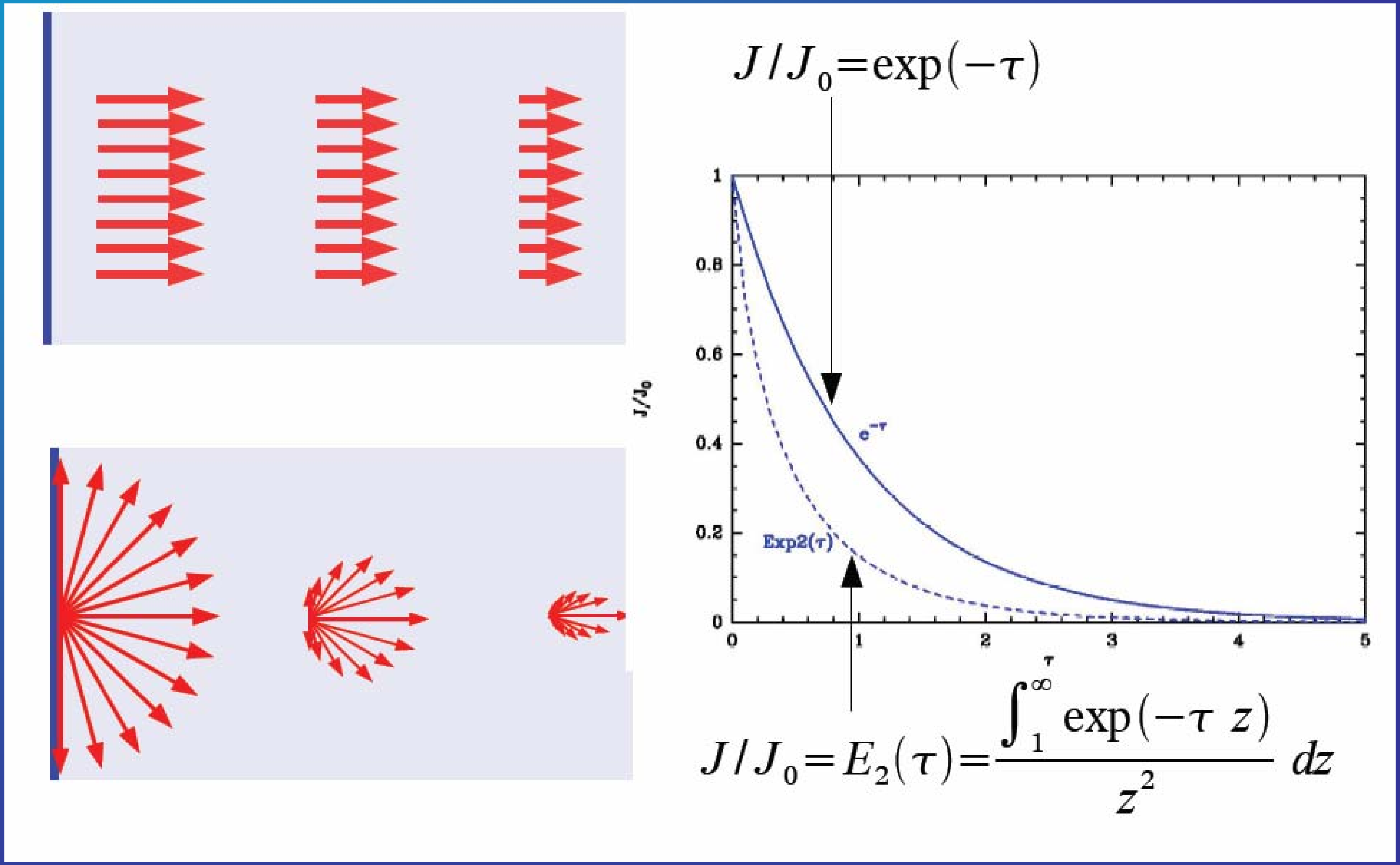
- The KOSMA-τ Code is designed to supply a large parameter grid of pre-calculated model clouds.
- results available per web-interface
- Standard parameters:
  D/G, n_0, M, χ, standard chemistry
- Extra: α, R_{core}, pre-shielding, σ_D, CR, Δv_D, X_i, chemical composition

The KOSMA-τ Code

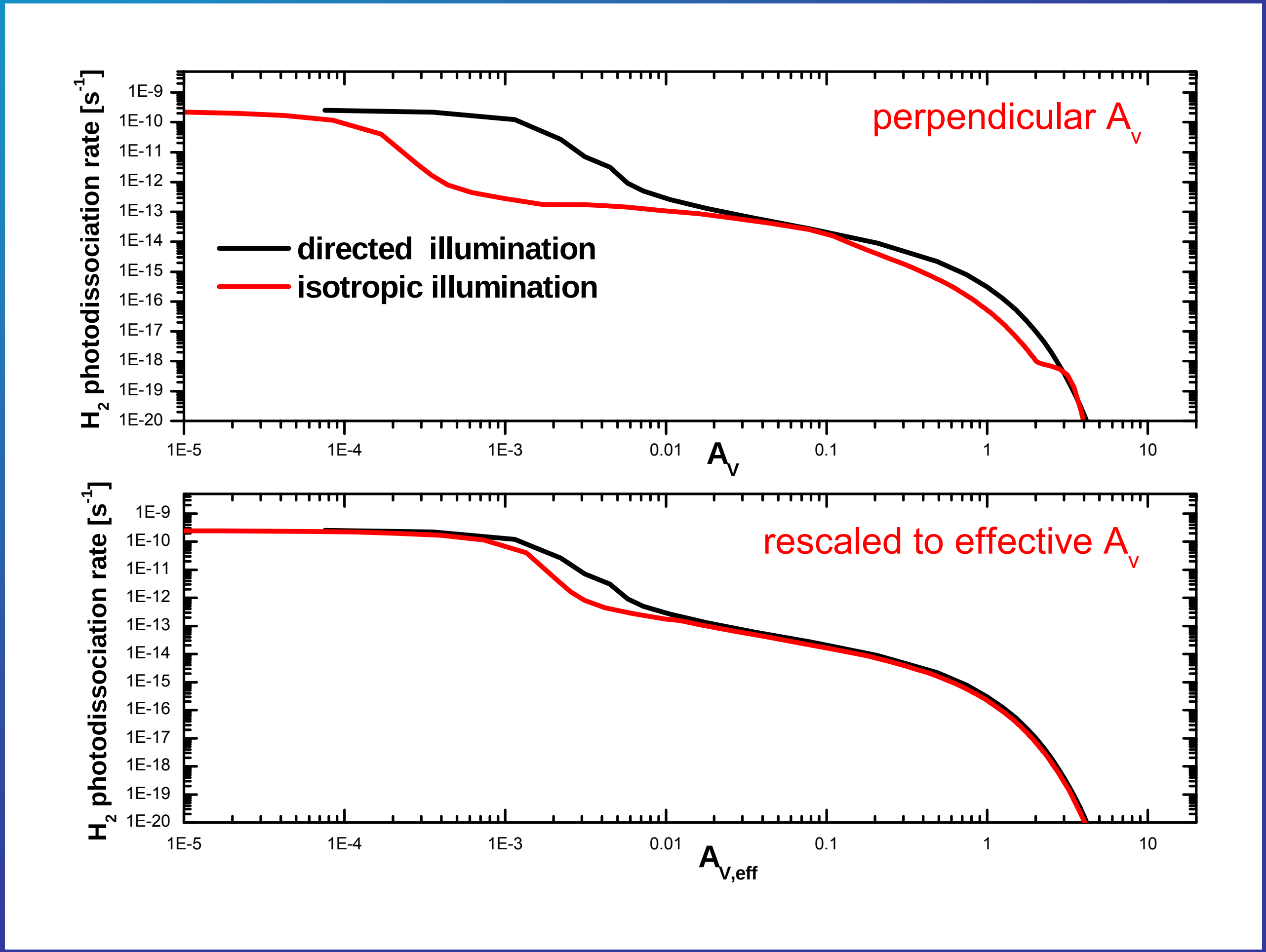


- •Introduction
- •The KOSMA-τ Code
- •Low Z PDRs
- •[CII]/CO(1-0)
- •[CI]/CO(1-0)
- •Clumpy PDRs
- •Modeling the MW
- •Summary

The KOSMA-τ Code



The KOSMA-τ Code



The KOSMA-τ Code

Solve chemical network

$$n_i \left\{ \tilde{\varsigma}_i + \sum_q n_q \cdot k_{qi}(T) \right\} = \sum_r \sum_s k_{rs}(T) \cdot n_r \cdot n_s + \sum_t n_t \cdot \tilde{\varsigma}_{ti}$$

destruction formation

The KOSMA-τ Code

Solve chemical network

$$n_i \left\{ \tilde{\varsigma}_i + \sum_q n_q \cdot k_{qi}(T) \right\} = \sum_r \sum_s k_{rs}(T) \cdot n_r \cdot n_s + \sum_t n_t \cdot \tilde{\varsigma}_{ti}$$

destruction formation

→ $\vec{n}(\vec{r})$

The KOSMA-τ Code

Solve chemical network

$$n_i \left\{ \tilde{\varsigma}_i + \sum_q n_q \cdot k_{qi}(T) \right\} = \sum_r \sum_s k_{rs}(T) \cdot n_r \cdot n_s + \sum_t n_t \cdot \tilde{\varsigma}_{ti}$$

destruction formation

→ $\vec{n}(\vec{r})$ ↓

Solve energy balance

$$\sum_i \Gamma_i(\vec{r}, \vec{n}, \chi, T) = \sum_i \Lambda_i(\vec{r}, \vec{n}, \chi, T)$$

heat cooling

- •Introduction
- •The KOSMA-τ Code
- •Low Z PDRs
- •[CII]/CO(1-0)
- •[CI]/CO(1-0)
- •Clumpy PDRs
- •Modeling the MW
- •Summary

The KOSMA-τ Code

Solve chemical network

$$n_i \left\{ \tilde{\varsigma}_i + \sum_q n_q \cdot k_{qi}(T) \right\} = \sum_r \sum_s k_{rs}(T) \cdot n_r \cdot n_s + \sum_t n_t \cdot \tilde{\varsigma}_{ti}$$

destruction formation

→ $\vec{n}(\vec{r})$

Solve energy balance

$$\sum_i \Gamma_i(\vec{r}, \vec{n}, \chi, T) = \sum_i \Lambda_i(\vec{r}, \vec{n}, \chi, T)$$

heat cooling

→ $T_{dust,gas}(\vec{r})$

The KOSMA-τ Code

- •Introduction
- •The KOSMA-τ Code
- •Low Z PDRs
- •[CII]/CO(1-0)
- •[CI]/CO(1-0)
- •Clumpy PDRs
- •Modeling the MW
- •Summary

Solve chemical network

$$n_i\left\{\tilde{\varsigma}_i + \sum_q n_q \cdot k_{qi}(T)\right\} = \sum_r \sum_s k_{rs}(T)\cdot n_r \cdot n_s + \sum_t n_t \cdot \tilde{\varsigma}_{ti}$$

destruction — formation

→ $\vec{n}(\vec{r})$

Solve energy balance

$$\sum_i \Gamma_i(\vec{r},\vec{n},\chi,T) = \sum_i \Lambda_i(\vec{r},\vec{n},\chi,T)$$

heat — cooling

→ $T_{dust,gas}(\vec{r})$

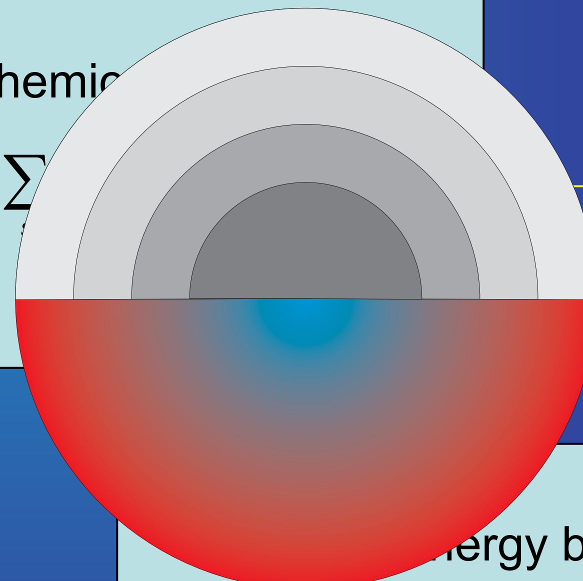
The KOSMA-τ Code

Solve chemic

$$n_i\left\{\tilde{\varsigma}_i+\sum_q n_q\cdot k_{qi}(T)\right\}=\sum_r\sum_s$$

destruction

$\vec{n}(\vec{r})$



ergy balance

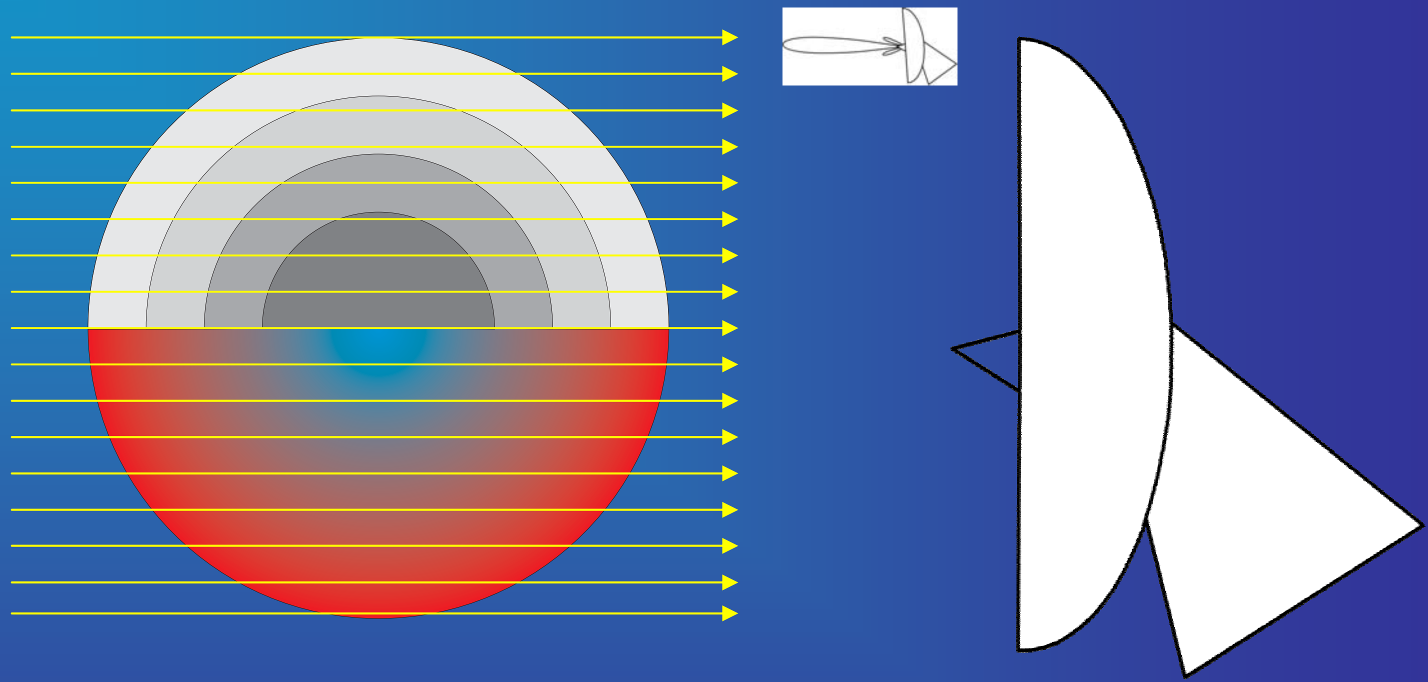
$$\sum_i\Gamma_i(\vec{r},\vec{n},\chi,T)=\sum_i\Lambda_i(\vec{r},\vec{n},\chi,T)$$

heat cooling

$T_{dust,gas}(\vec{r})$

- Introduction
- The KOSMA-τ Code
- Low Z PDRs
- [CII]/CO(1-0)
- [CI]/CO(1-0)
- Clumpy PDRs
- Modeling the MW
- Summary

The KOSMA-τ Code



Radiative Transfer Calculations
multi-shell ray-tracing ONION, SimLine, etc.
calculates emergent intensities per beam
and averaged over the whole clump

Low Z-PDRs

Theory and observations suggest that metallicity Z significantly changes the structure of PDR's :

- altered Z $\rightarrow$ altered gas-phase chemistry
- altered Z $\rightarrow$ less dust
  - altered grain surface chemistry (e.g. formation of H_2)
  - weaker extinction $\rightarrow$ deeper FUV penetration $\rightarrow$ stronger photo-reactions
- altered Z $\rightarrow$ altered heating/cooling rates $\rightarrow$ altered $T_{equil.}$
- dissociation/formation of H_2 and CO change differently with Z $\rightarrow$ standard X_{CO} factors yield incorrect results $\rightarrow$ molecular gas in low-Z systems not well traced by CO.

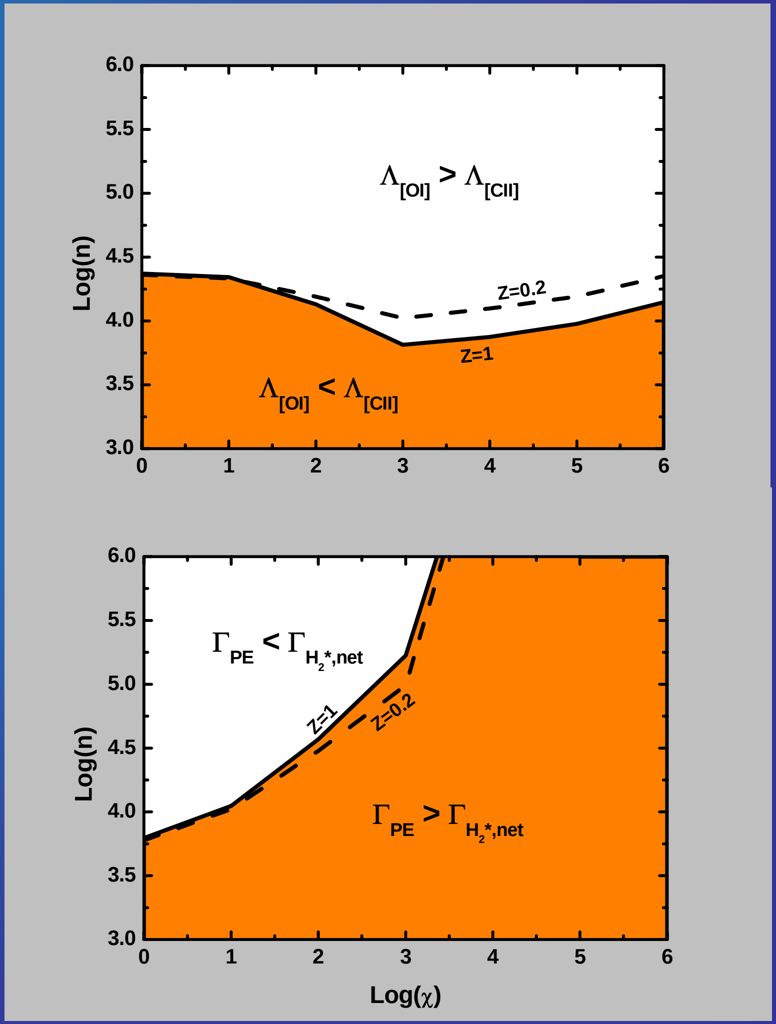
$\rightarrow$ **temperature structure and chemical stratification depend on metallicity**

Low Z PDRs

Temperature determined by balancing heating and cooling

At the Surface:
4 primary h/c processes:

- PE heating
- H2 vib. de-excitation
- [CII] 158µm fine-structure cooling
- [OI] 63µm fine-structure cooling

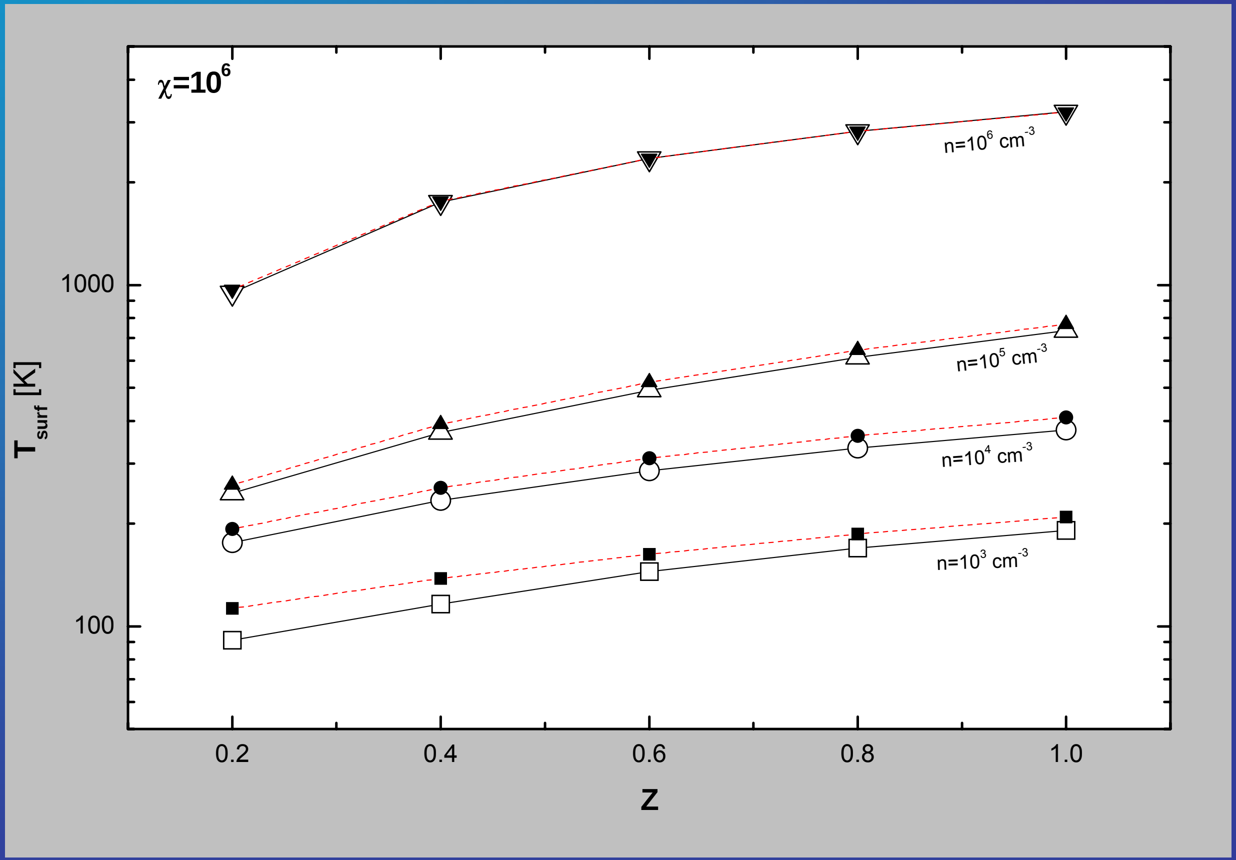


Low Z PDRs

n ↑, χ →

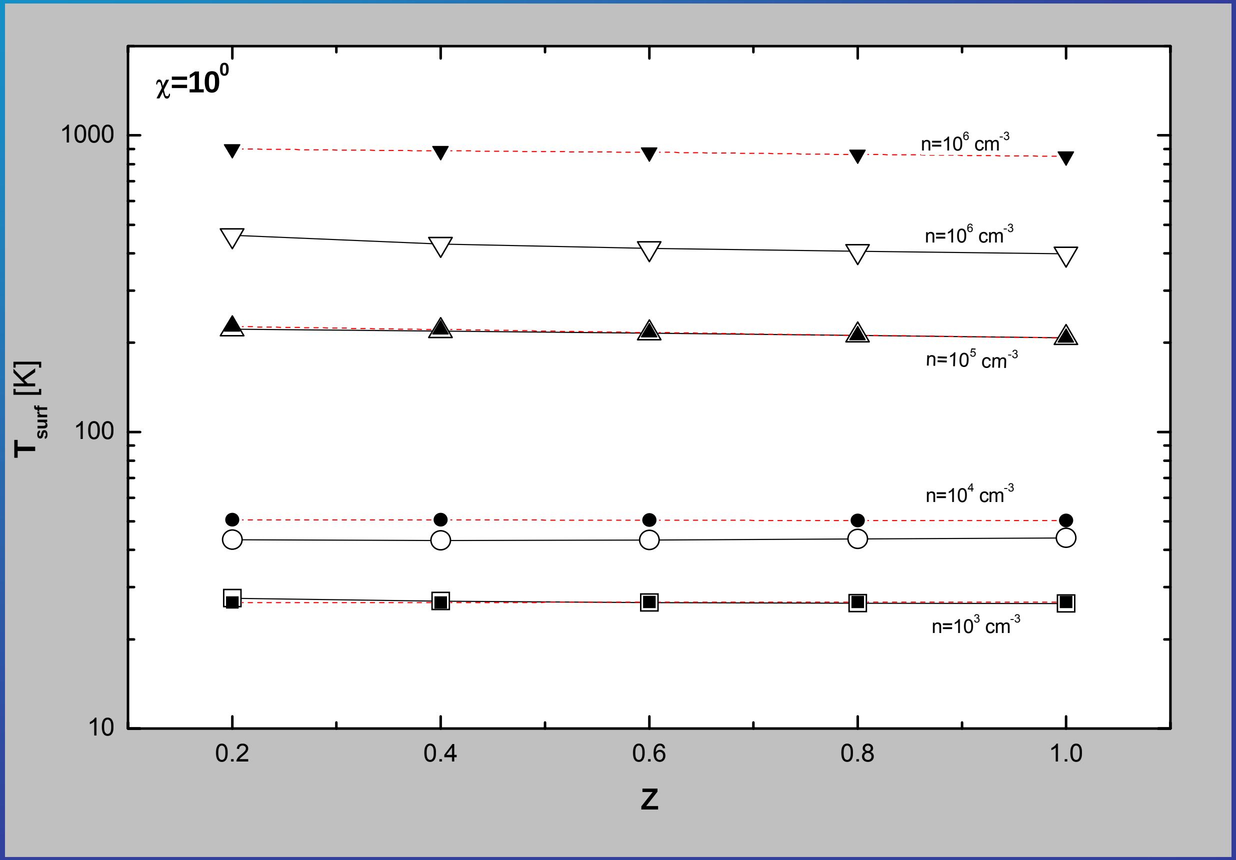
$\Lambda_{[OI]} \gg \Lambda_{[CII]}$ $\Gamma_{PE} \ll \Gamma_{H_2^*}$ $\Gamma_{PE} \sim Z$ $\Gamma_{H_2^*} \sim Z/(1+2Z)$ $T \sim 1/(1+2Z)$	$\Lambda_{[OI]} \gg \Lambda_{[CII]}$ $\Gamma_{PE} \gg \Gamma_{H_2^*}$ $\Gamma_{PE} \sim Z^2$ $\Gamma_{H_2^*} \sim Z$ $T \sim Z$
$\Lambda_{[OI]} \ll \Lambda_{[CII]}$ $\Gamma_{PE} \gg \Gamma_{H_2^*}$ $\Gamma_{PE} \sim Z$ $\Gamma_{H_2^*} \sim Z$ $T \sim \text{const.}$	$\Lambda_{[OI]} \ll \Lambda_{[CII]}$ $\Gamma_{PE} \gg \Gamma_{H_2^*}$ $\Gamma_{PE} \sim Z \ldots Z^{1.5}$ $\Gamma_{H_2^*} \sim Z$ $T \sim Z^{0.5} \ldots Z$

Low Z PDRs

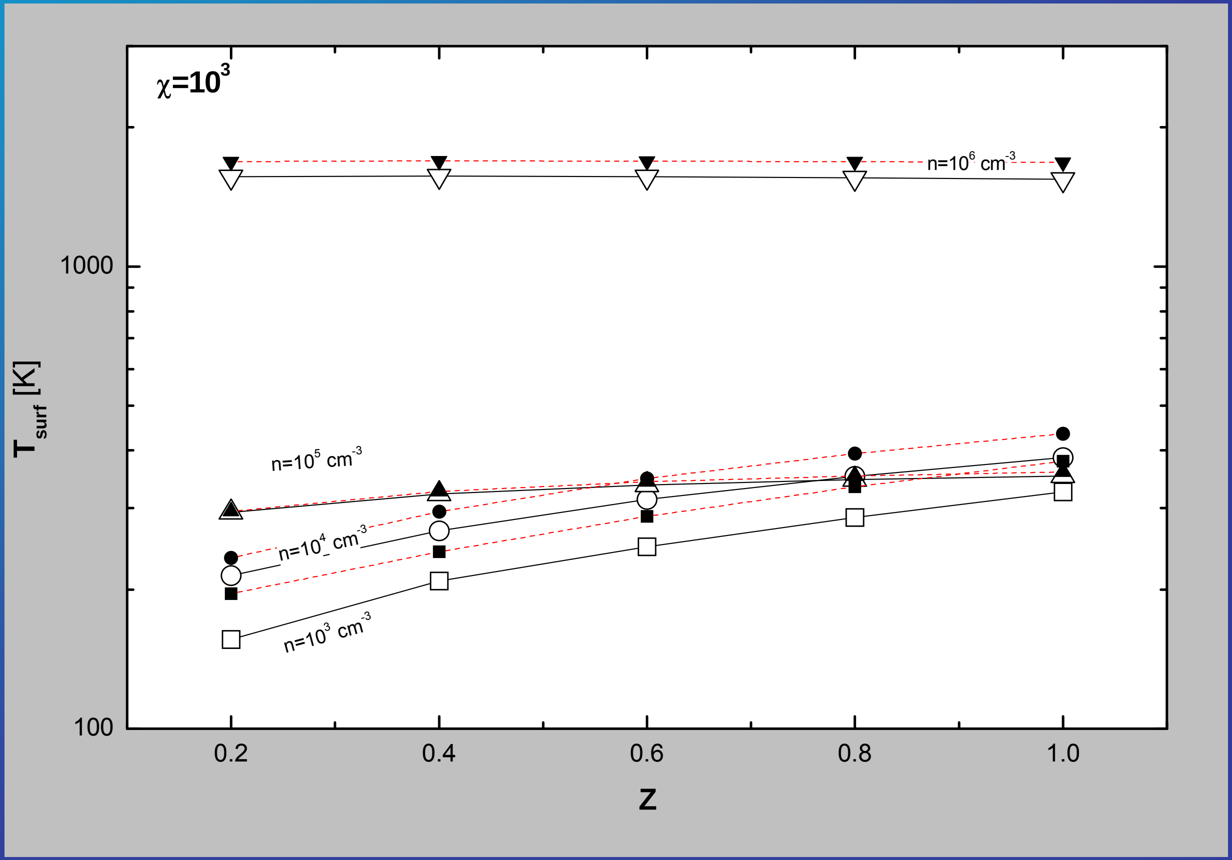


χ=10^6
n=10^6 cm^-3
n=10^5 cm^-3
n=10^4 cm^-3
n=10^3 cm^-3
1000
100
T_surf [K]
0.2
0.4
0.6
0.8
1.0
Z

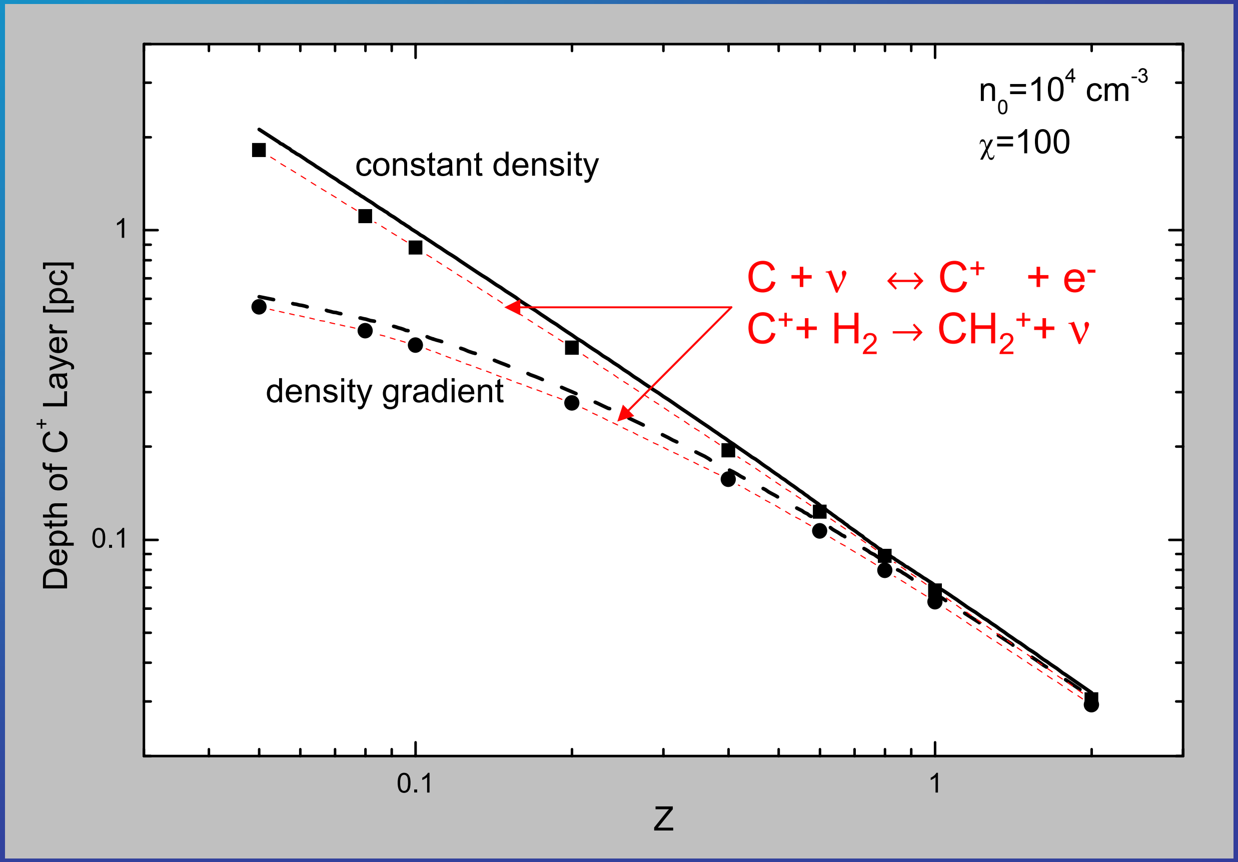
Low Z PDRs


χ=10^0
1000
100
10
T_{surf} [K]
n=10^6 cm^-3
n=10^6 cm^-3
n=10^5 cm^-3
n=10^4 cm^-3
n=10^3 cm^-3
0.2
0.4
0.6
0.8
1.0
Z

Low Z PDRs


χ=10^3
n=10^6 cm^-3
n=10^5 cm^-3
n=10^4 cm^-3
n=10^3 cm^-3
1000
100
T_surf [K]
0.2
0.4
0.6
0.8
1.0
Z

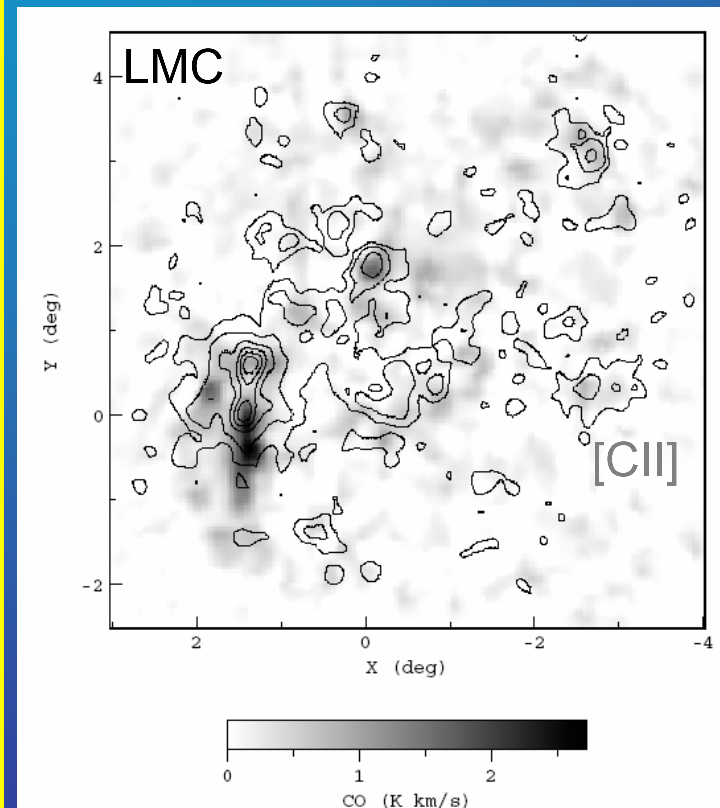
Low Z PDRs

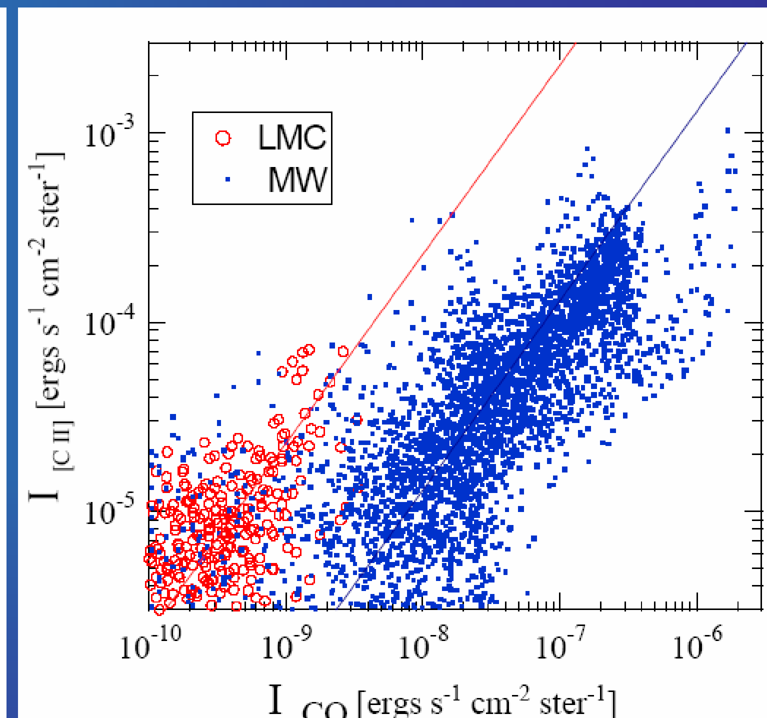


$n_0=10^4$ cm^{-3}
$\chi=100$
constant density
density gradient
$C + \nu \leftrightarrow C^+ + e^-$
$C^+ + H_2 \rightarrow CH_2^+ + \nu$
Depth of C^+ Layer [pc]
1
0.1
0.1
1
Z

- Introduction
- The KOSMA-τ Code
- Low Z PDRs
- [CII]/CO(1-0)
- [CI]/CO(1-0)
- Clumpy PDRs
- Modeling the MW
- Summary

[CII]/CO(1-0)



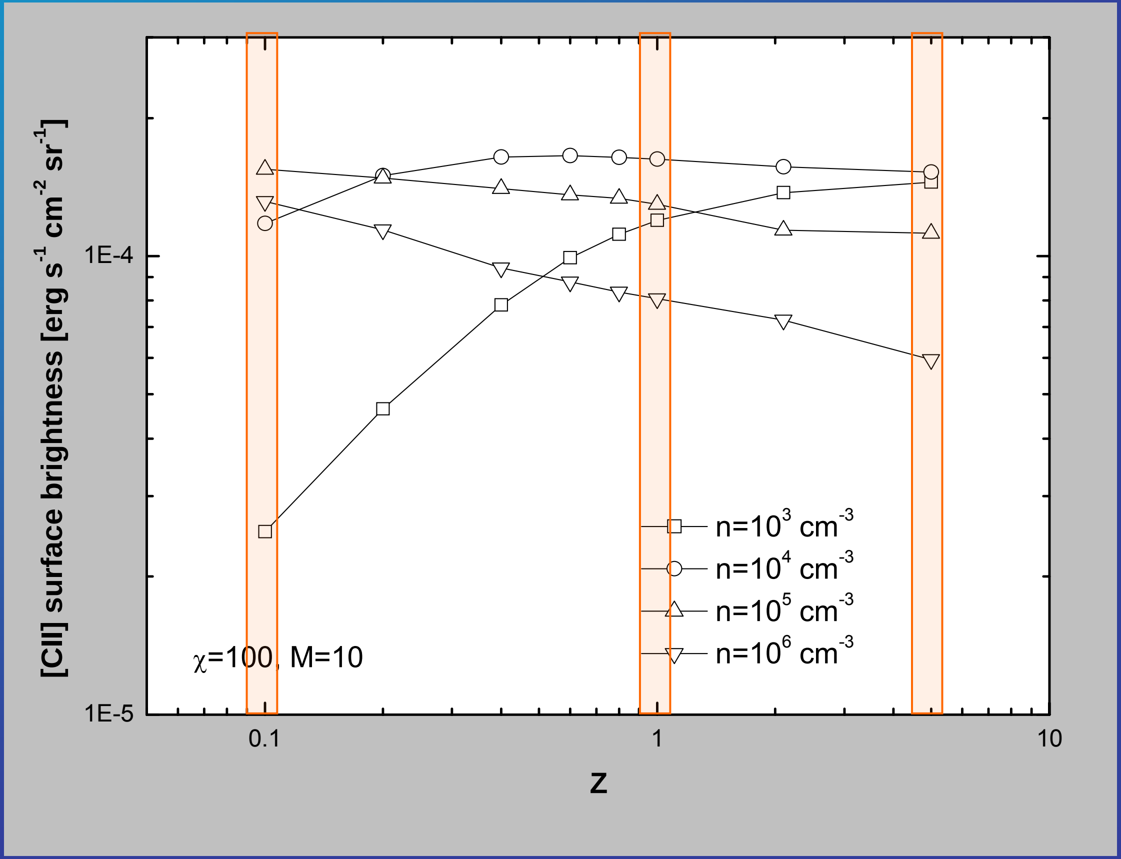


Nakagawa et al. 2005

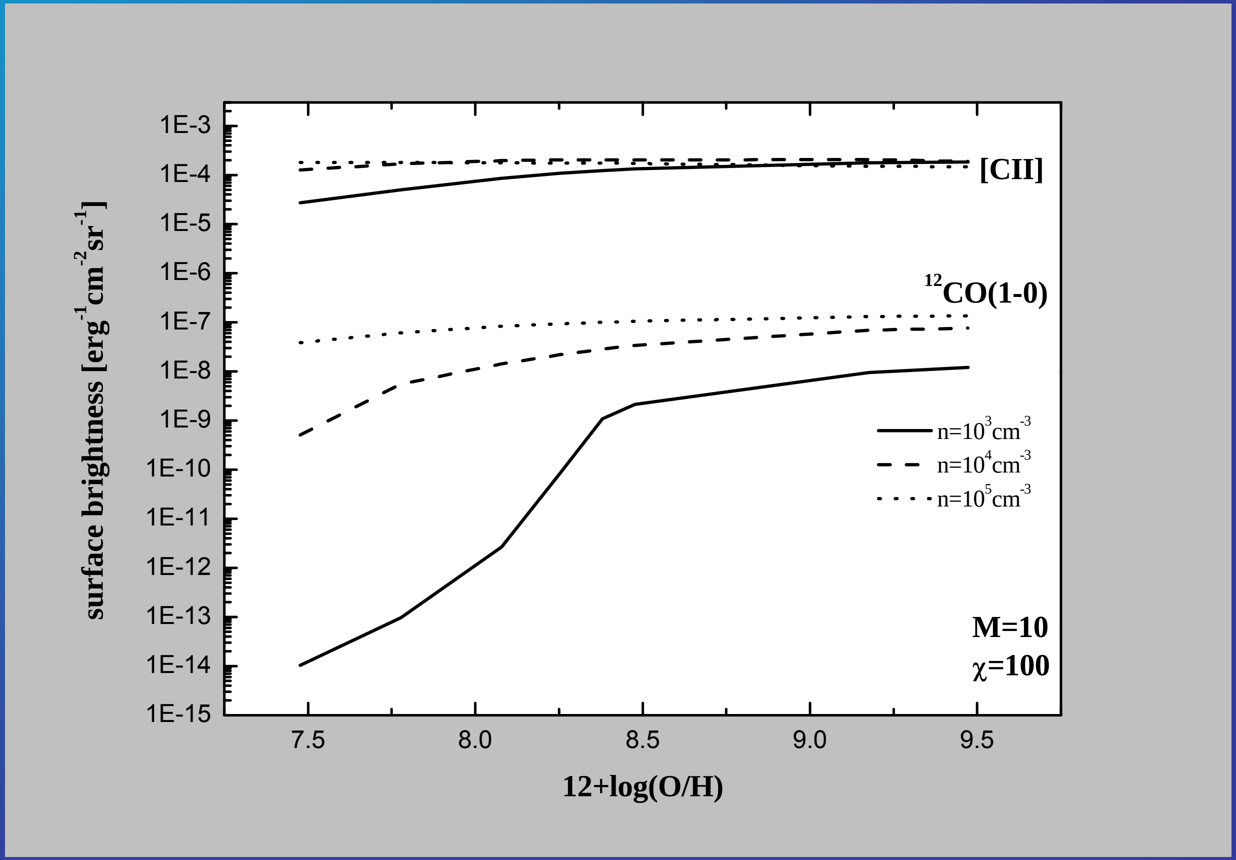
[CII]/CO(1-0)

- Introduction
- The KOSMA-τ Code
- Low Z PDRs
- [CII]/CO(1-0)
- [CI]/CO(1-0)
- Clumpy PDRs
- Modeling the MW
- Summary

line integrated, clump averaged surface brightness of [CII]158µm



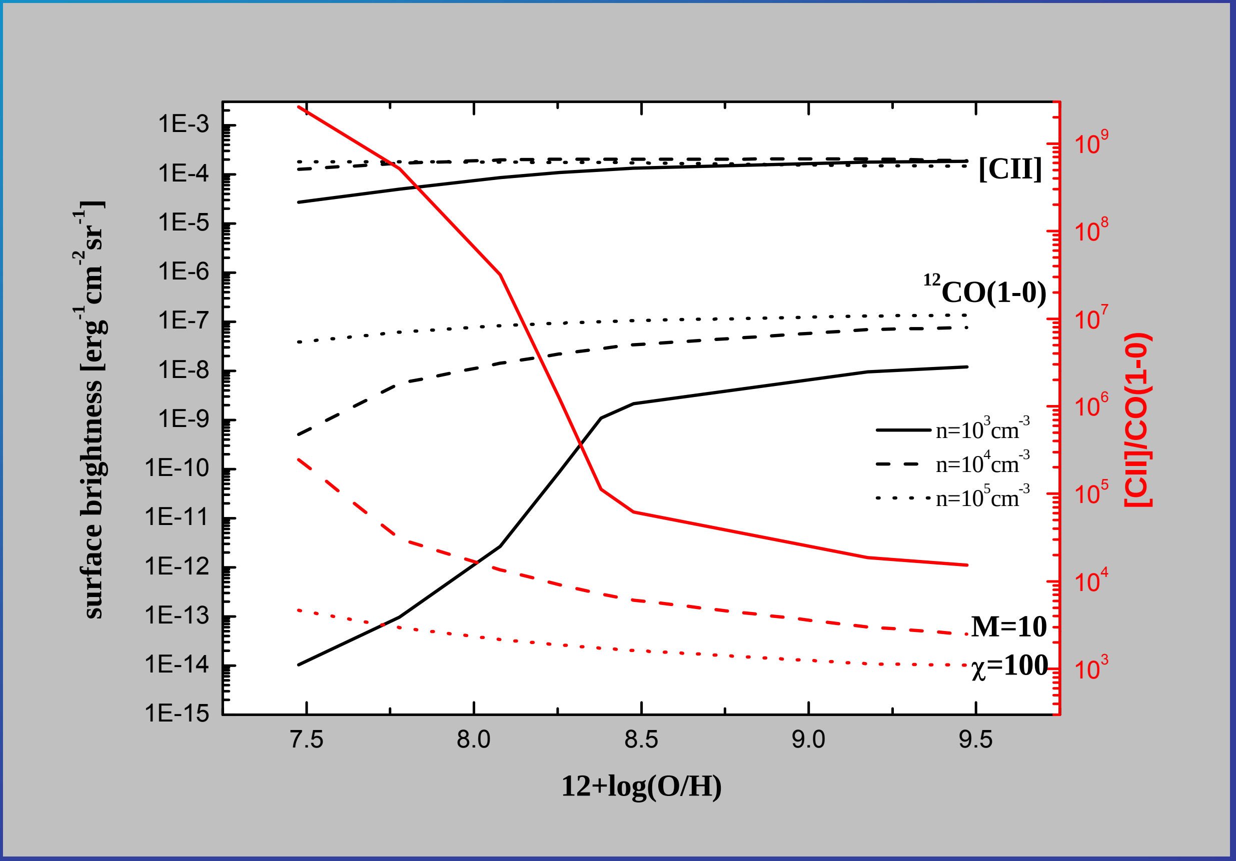
[CII]/CO(1-0)



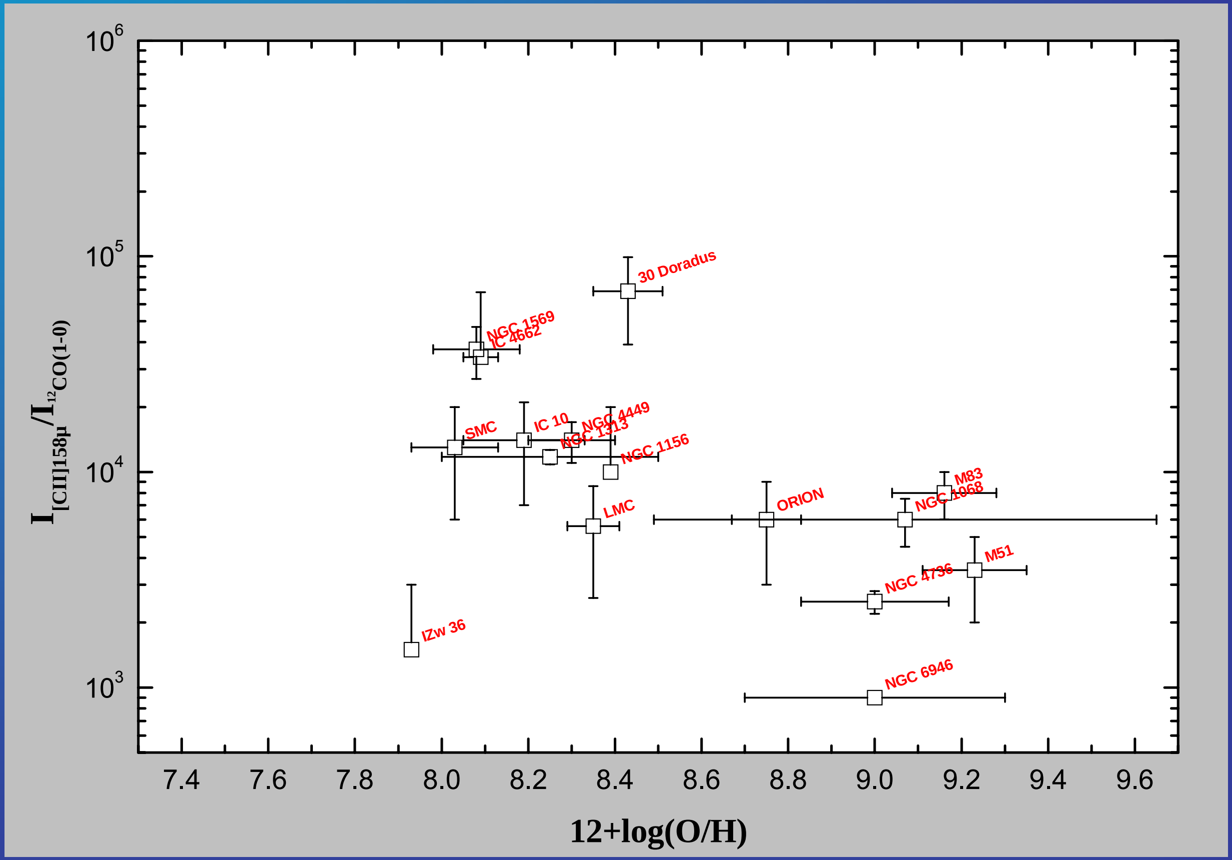
[CII]
12CO(1-0)
n=10³cm⁻³
n=10⁴cm⁻³
n=10⁵cm⁻³
M=10
χ=100
surface brightness [erg cm⁻² sr⁻¹]
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
1E-11
1E-12
1E-13
1E-14
1E-15
7.5
8.0
8.5
9.0
9.5
12+log(O/H)

[CII]/CO(1-0)

- •Introduction
- •The KOSMA-τ Code
- •Low Z PDRs
- •[CII]/CO(1-0)
- •[CI]/CO(1-0)
- •Clumpy PDRs
- •Modeling the MW
- •Summary



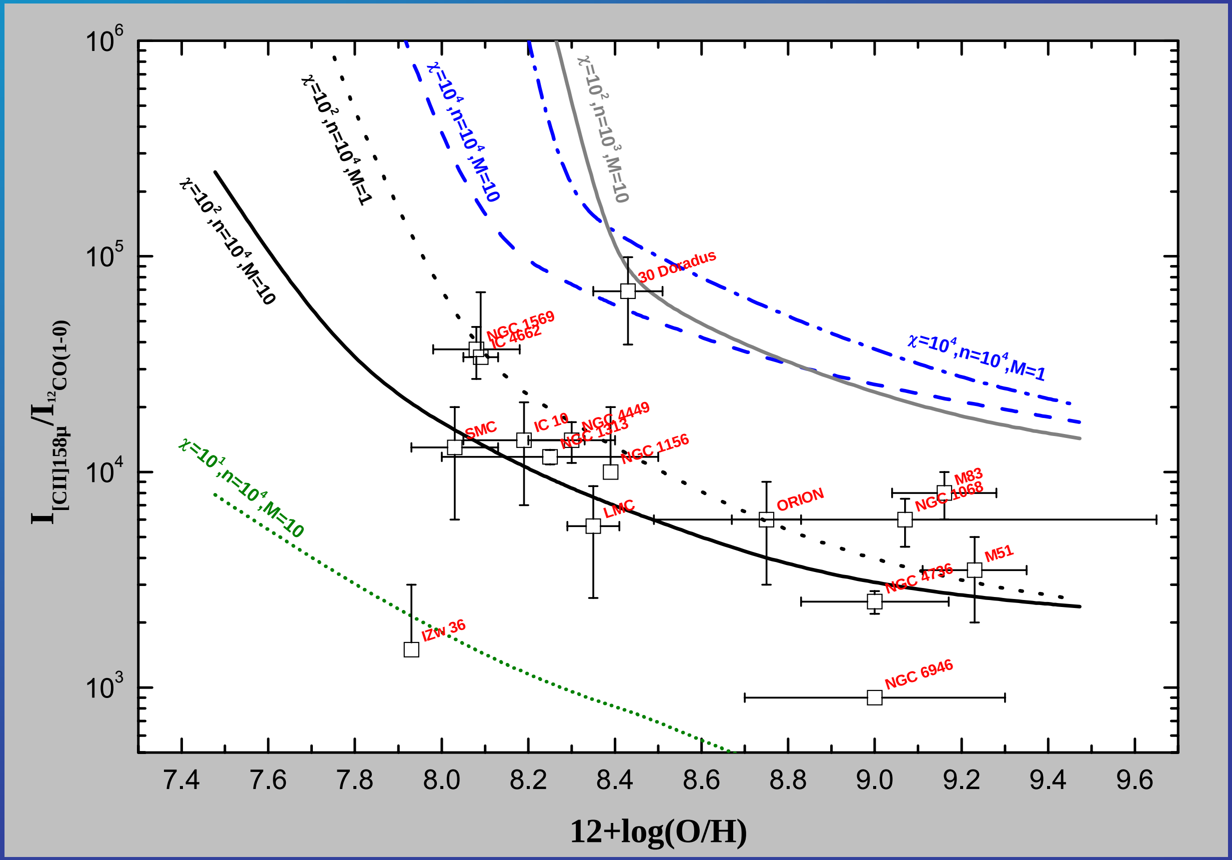
[CII]/CO(1-0)



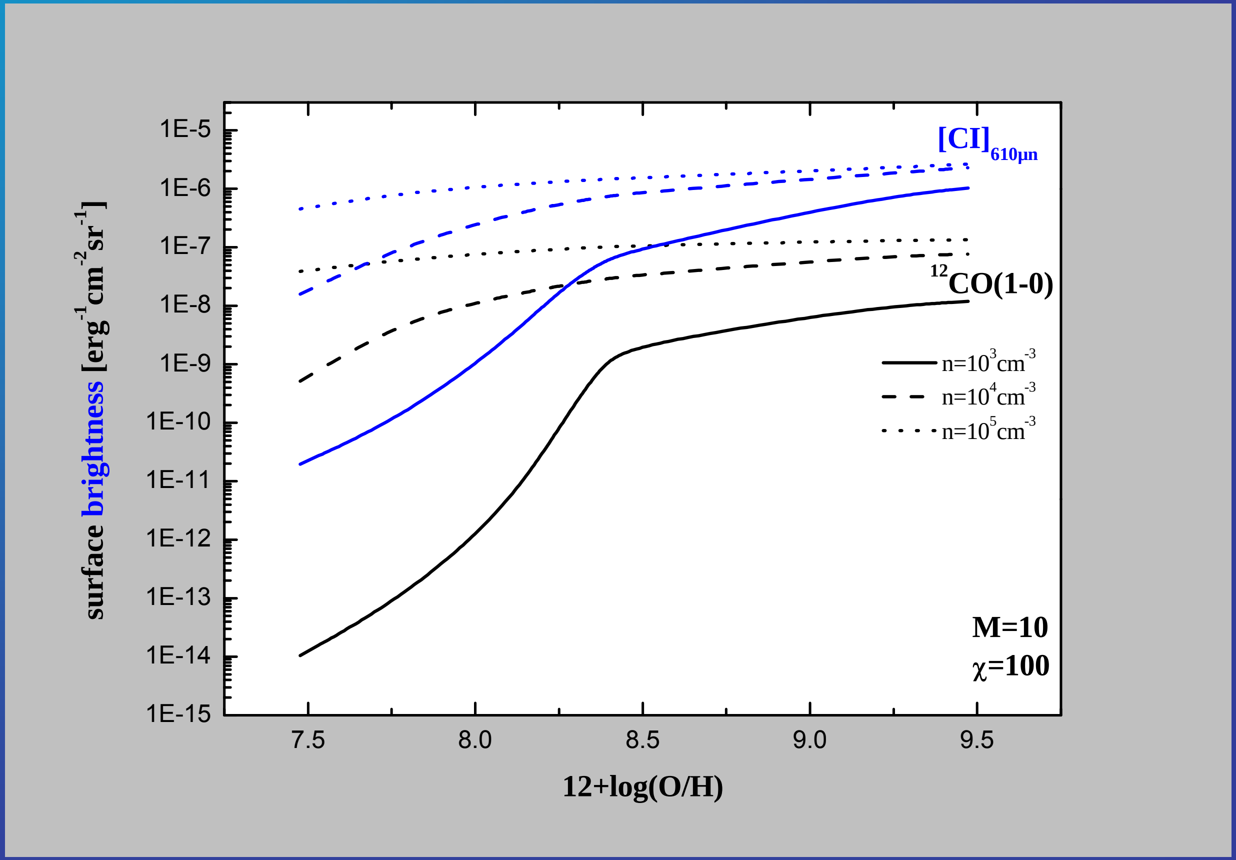
10^6
10^5
10^4
10^3
$I_{[CII]158\mu}/I_{^{12}CO(1-0)}$
7.4
7.6
7.8
8.0
8.2
8.4
8.6
8.8
9.0
9.2
9.4
9.6
12+log(O/H)
30 Doradus
NGC 1569
IC 4662
SMC
IC 10
NGC 4449
NGC 1313
NGC 1156
LMC
ORION
M83
NGC 1068
M51
NGC 4736
IZw 36
NGC 6946

[CII]/CO(1-0)

- •Introduction
- •The KOSMA-τ Code
- •Low Z PDRs
- •[CII]/CO(1-0)
- •[CI]/CO(1-0)
- •Clumpy PDRs
- •Modeling the MW
- •Summary

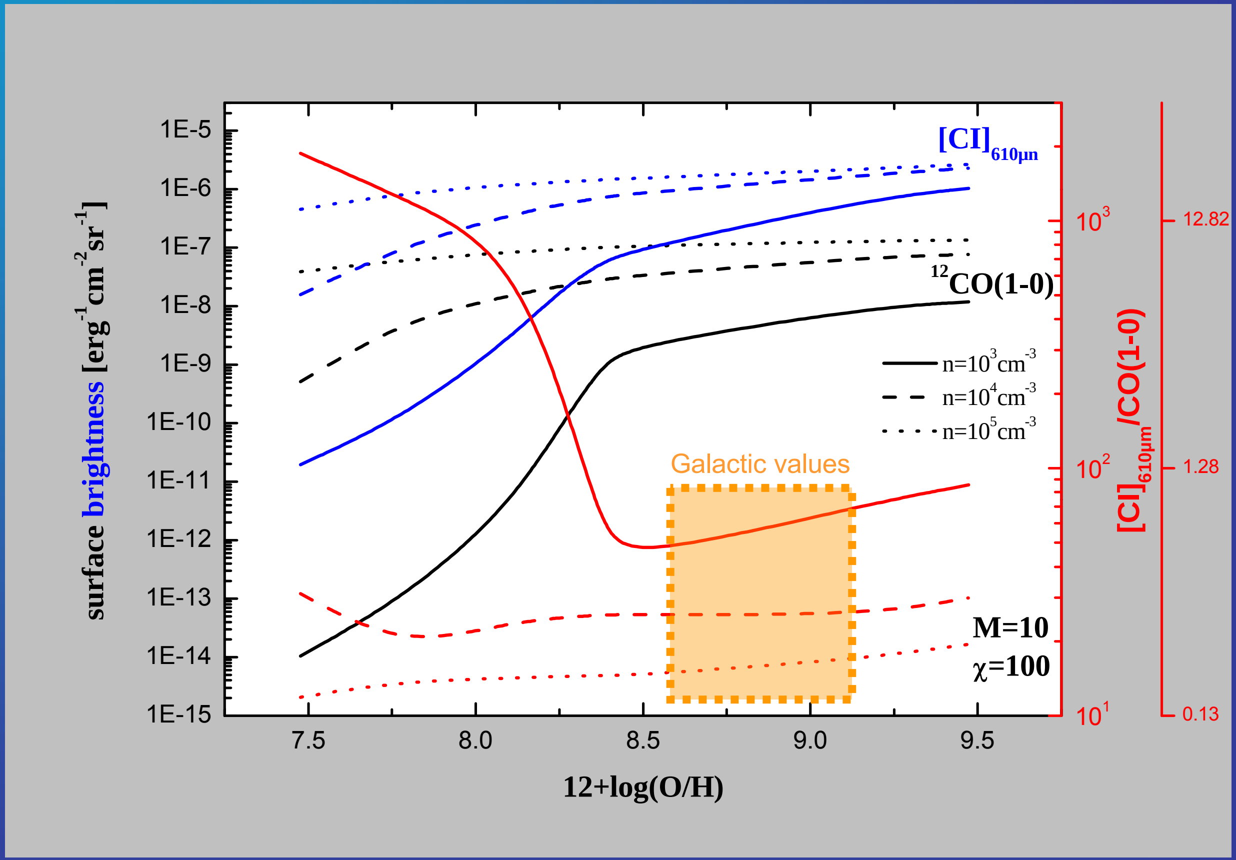


$[CI]_{610\mu m}/CO(1\text{-}0)$



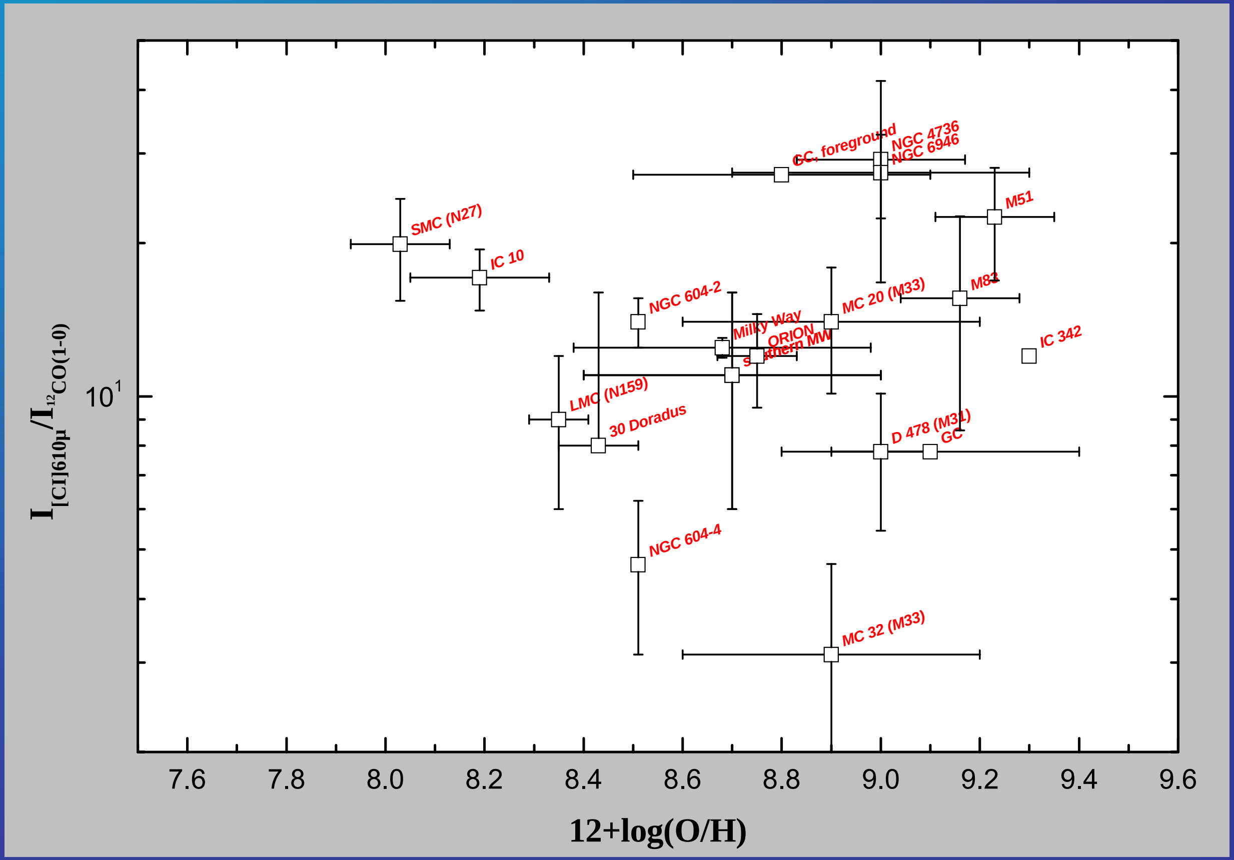
$[CI]_{610\mu m}/CO(1\text{-}0)$

- Introduction
- The KOSMA-τ Code
- Low Z PDRs
- [CII]/CO(1-0)
- [CI]/CO(1-0)
- Clumpy PDRs
- Modeling the MW
- Summary



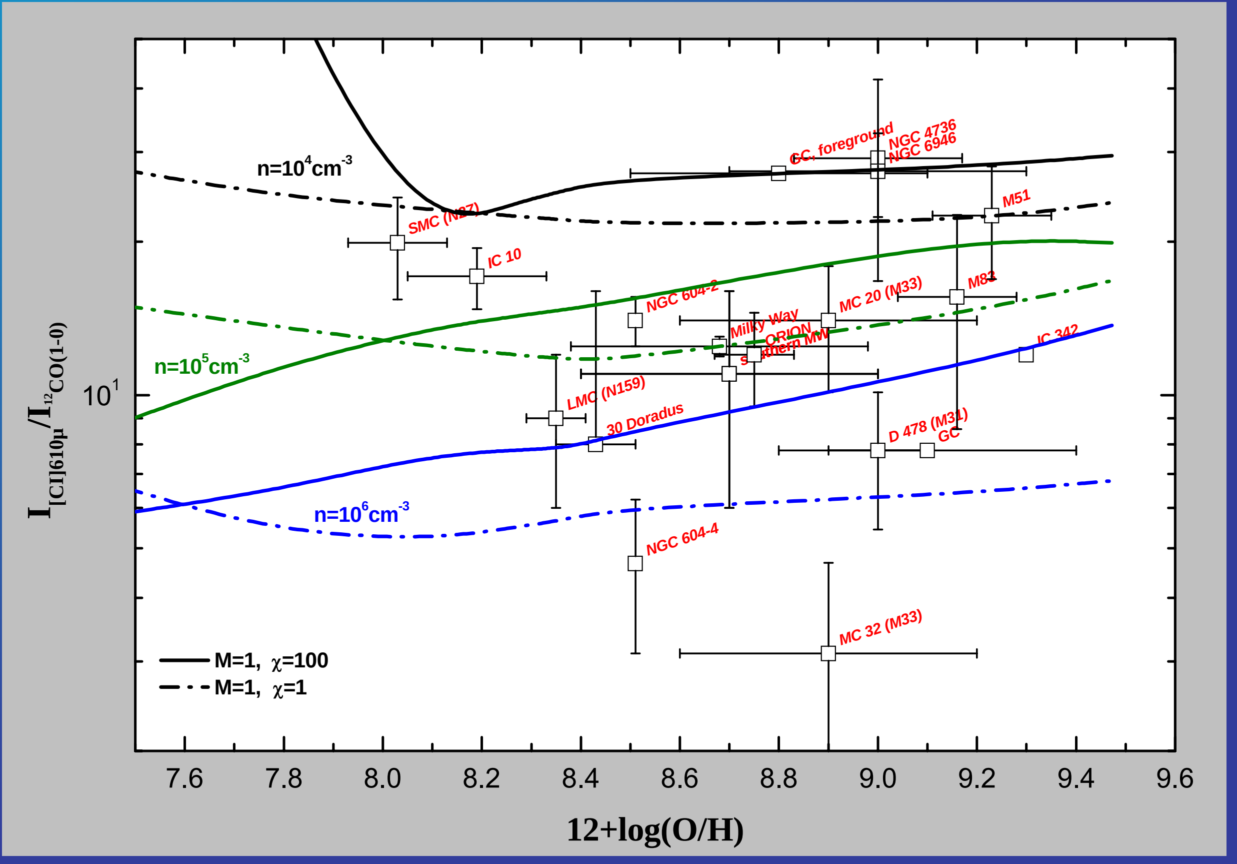
$[CI]_{610\mu m}/CO(1\text{-}0)$

- •Introduction
- •The KOSMA-τ Code
- •Low Z PDRs
- •[CII]/CO(1-0)
- •[CI]/CO(1-0)
- •Clumpy PDRs
- •Modeling the MW
- •Summary

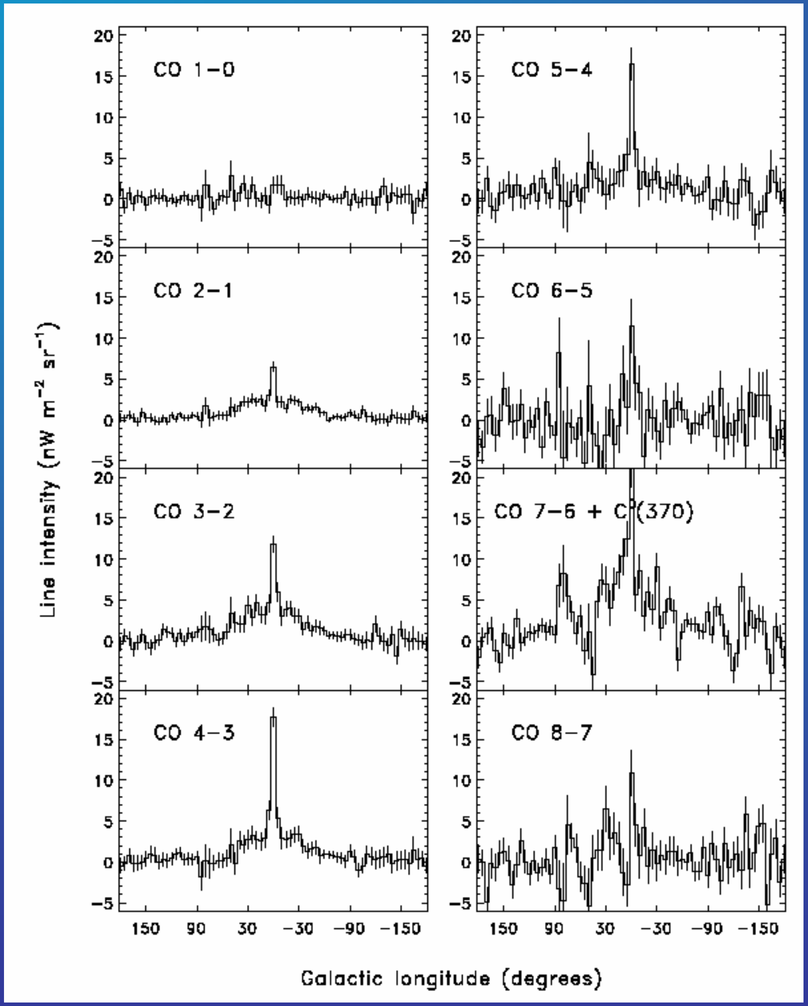


$[CI]_{610\mu m}/CO(1\text{-}0)$

- •Introduction
- •The KOSMA-τ Code
- •Low Z PDRs
- •[CII]/CO(1-0)
- •[CI]/CO(1-0)
- •Clumpy PDRs
- •Modeling the MW
- •Summary



Modeling the MW

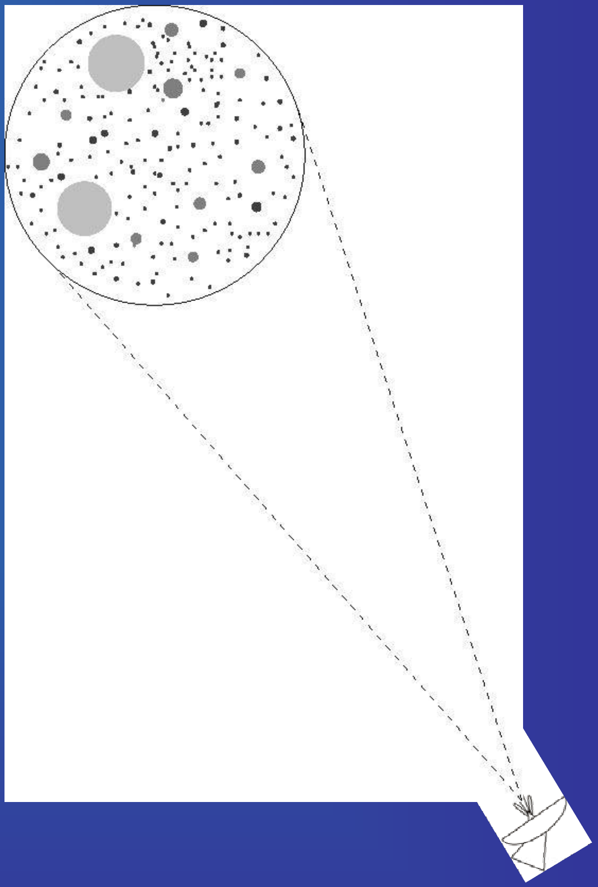


COBE-FIRAS: far-infrared survey of the spectral line emission from the Galaxy with a 7° beam

(Fixsen et al. 1999)

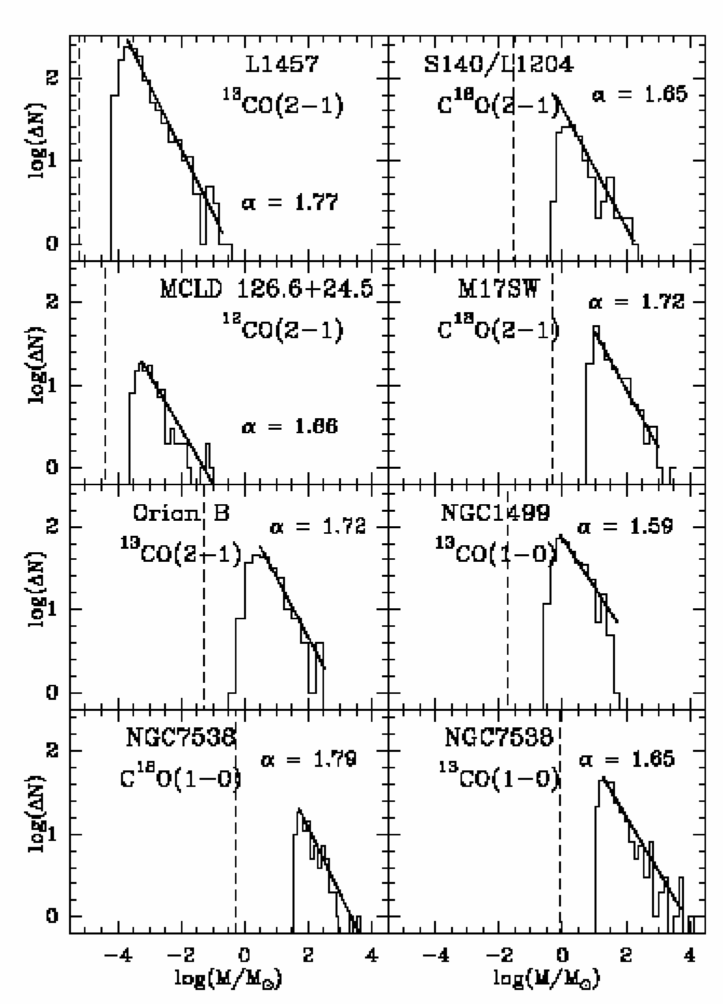
Modeling the MW

- a single, spherical clump scenario is a very special case
- usually molecular clouds have a highly irregular, clumpy structure, far from simple plane-parallel or spherical model clouds
- furthermore, molecular clouds are embedded in atomic gas, also contributing to the total emission



Modeling the MW

- observations show an almost universal clump-mass distribution with $dN/dM \propto M^{-1.6...1.8}$ and a mass-size relation of $M \propto R^{2.3}$



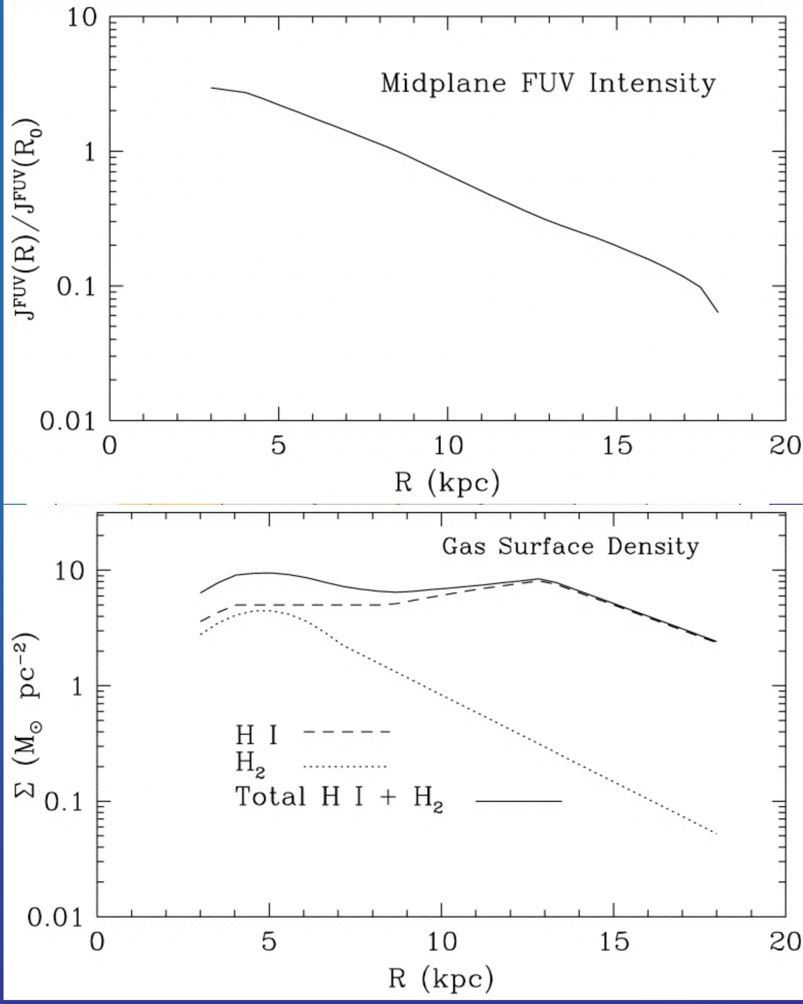
(Kramer et al. 1998)

- •Introduction
- •The KOSMA-τ Code
- •Low Z PDRs
- •[CII]/CO(1-0)
- •[CI]/CO(1-0)
- •Clumpy PDRs
- •Modeling the MW
- •Summary

Modeling the MW

- MW as disk with R_{tot}=18kpc and h=59pc
- *n*, χ, and *Z* as function of galactocentric radius (Wolfire et al. 2003)
- $n(R_\odot)=10^4 cm^{-3}$, $\chi(R_\odot)=3$
- molecular gas distributed according to C-M and M-S relation
- COBE beam (1°×5°)
- area- and volume filling per concentric ring

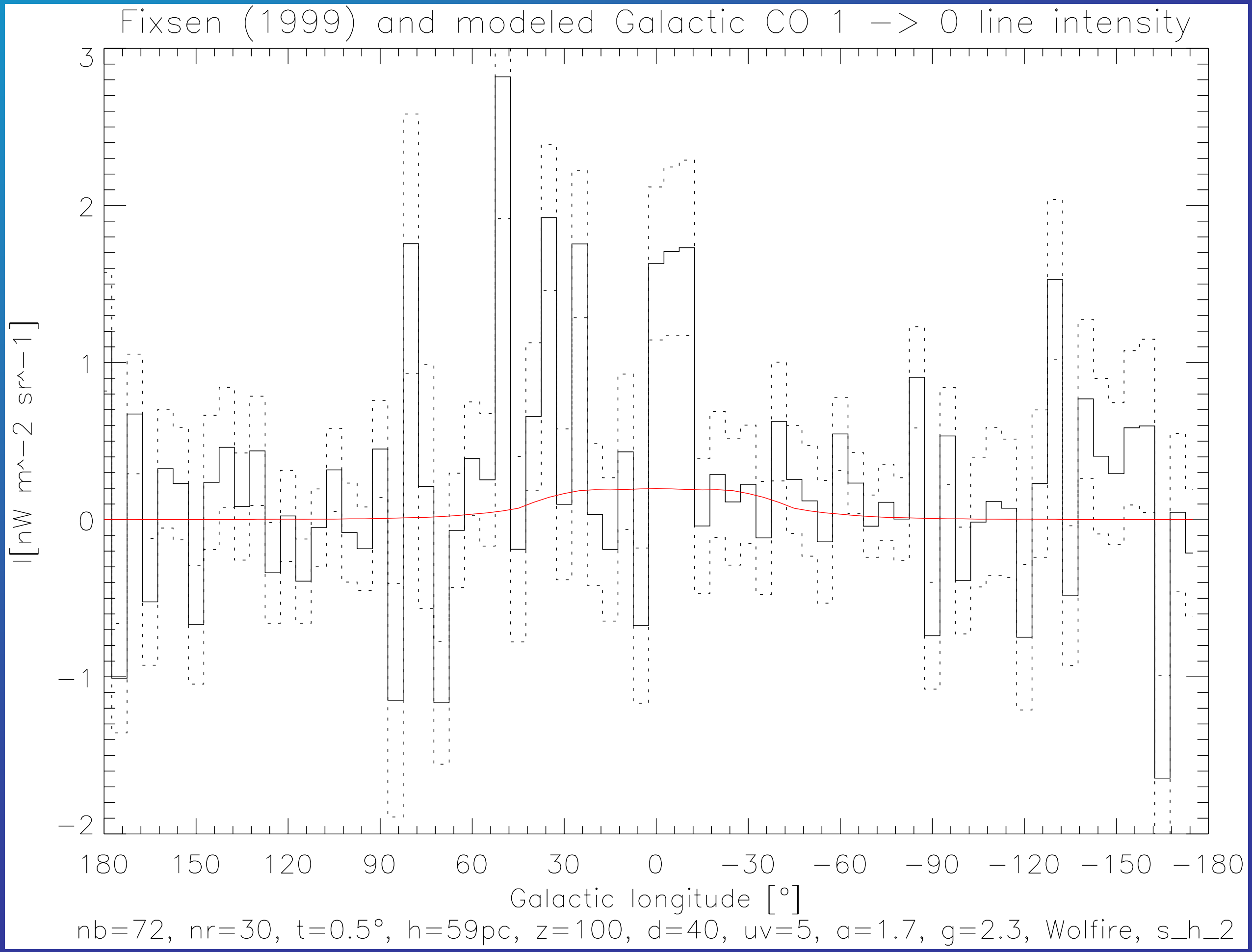
Credit: NASA/JPL-Caltech/R. Hurt (SSC)



(Fixsen et al. 1999)

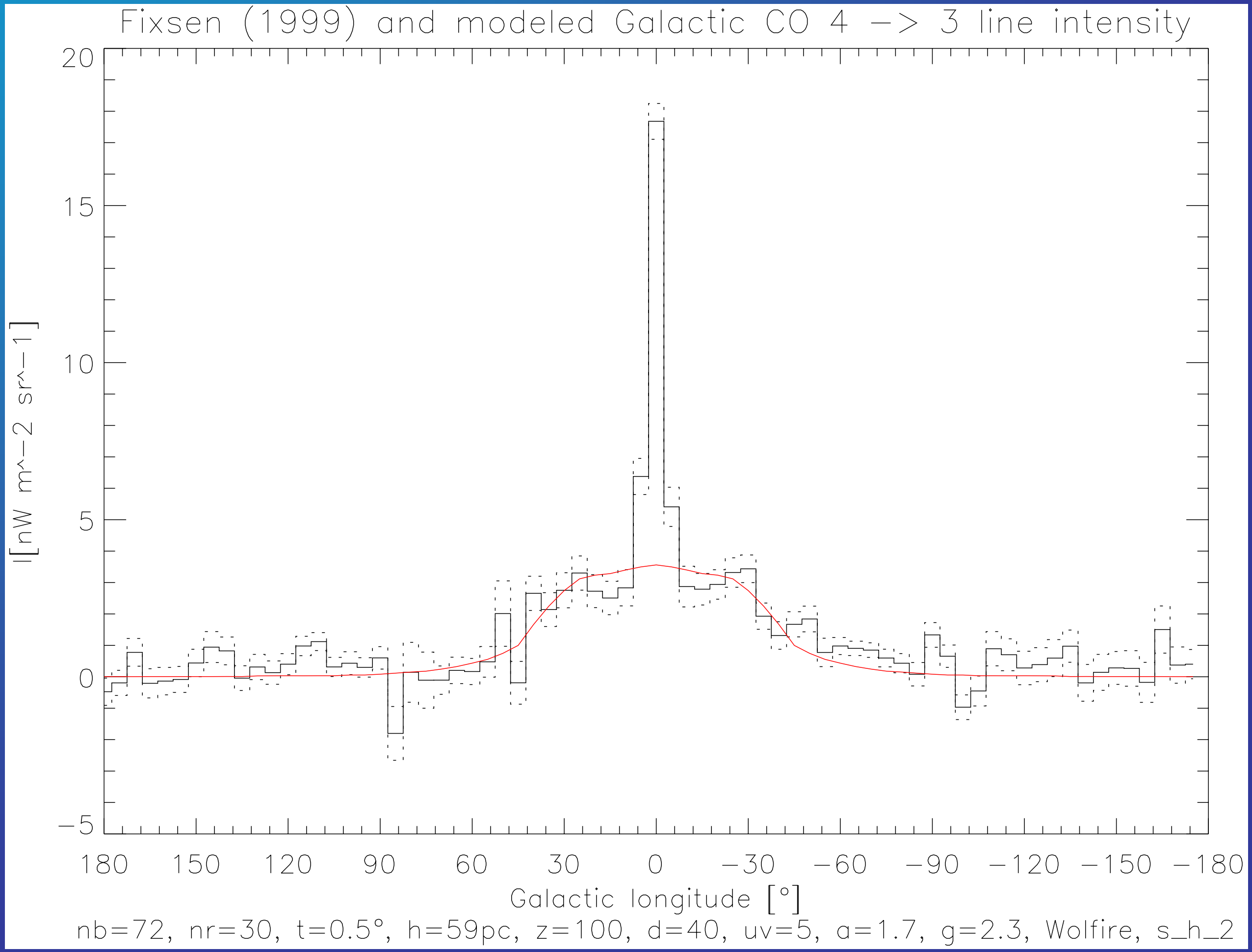
Modeling the MW

- •Introduction
- •The KOSMA-τ Code
- •Low Z PDRs
- •[CII]/CO(1-0)
- •[CI]/CO(1-0)
- •Clumpy PDRs
- •Modeling the MW
- •Summary



Modeling the MW

- •Introduction
- •The KOSMA-τ Code
- •Low Z PDRs
- •[CII]/CO(1-0)
- •[CI]/CO(1-0)
- •Clumpy PDRs
- •Modeling the MW
- •Summary



•Introduction

•The KOSMA-τ Code

•Low Z PDRs

•[CII]/CO(1-0)

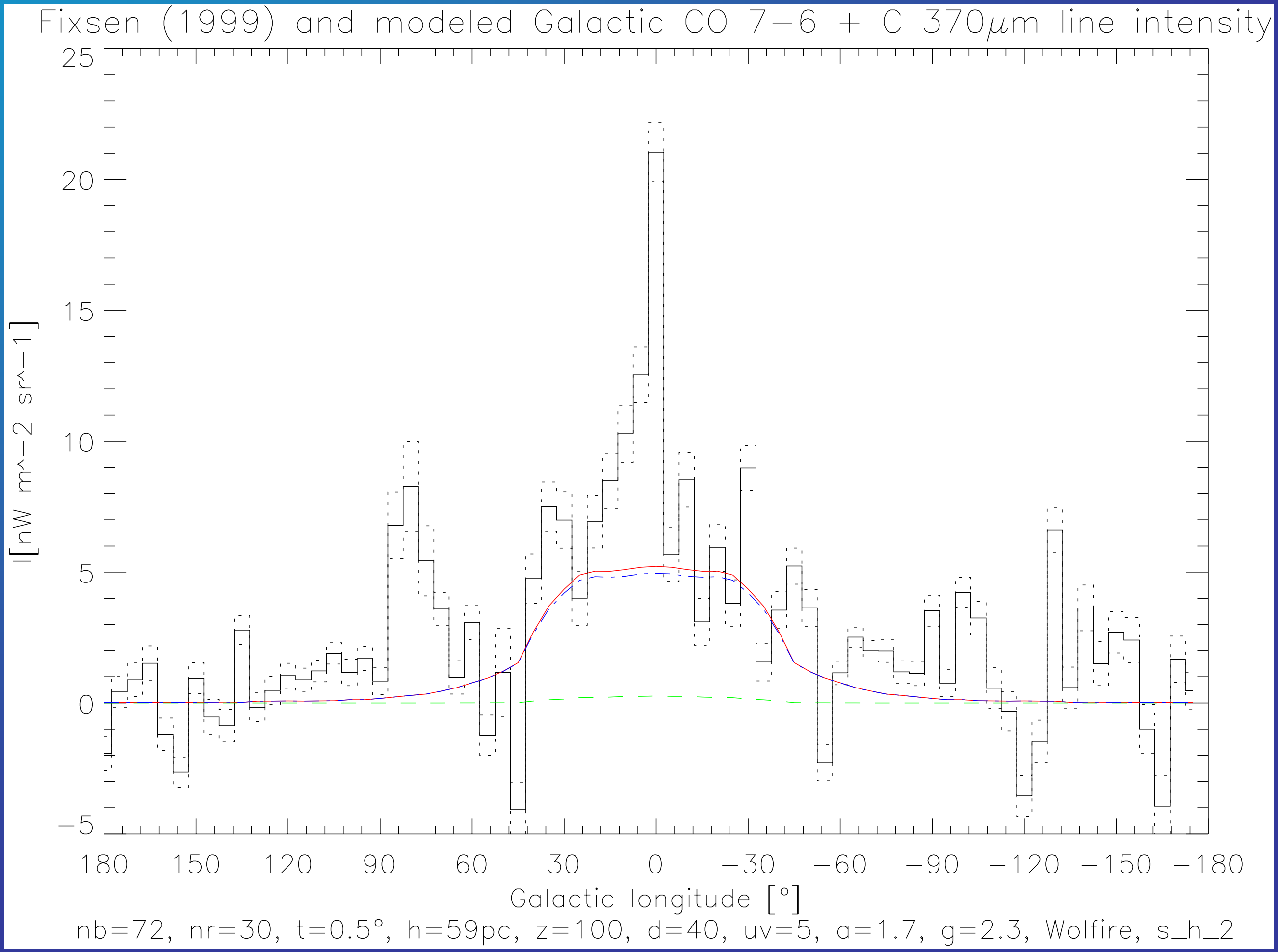
•[CI]/CO(1-0)

•Clumpy PDRs

•Modeling the MW

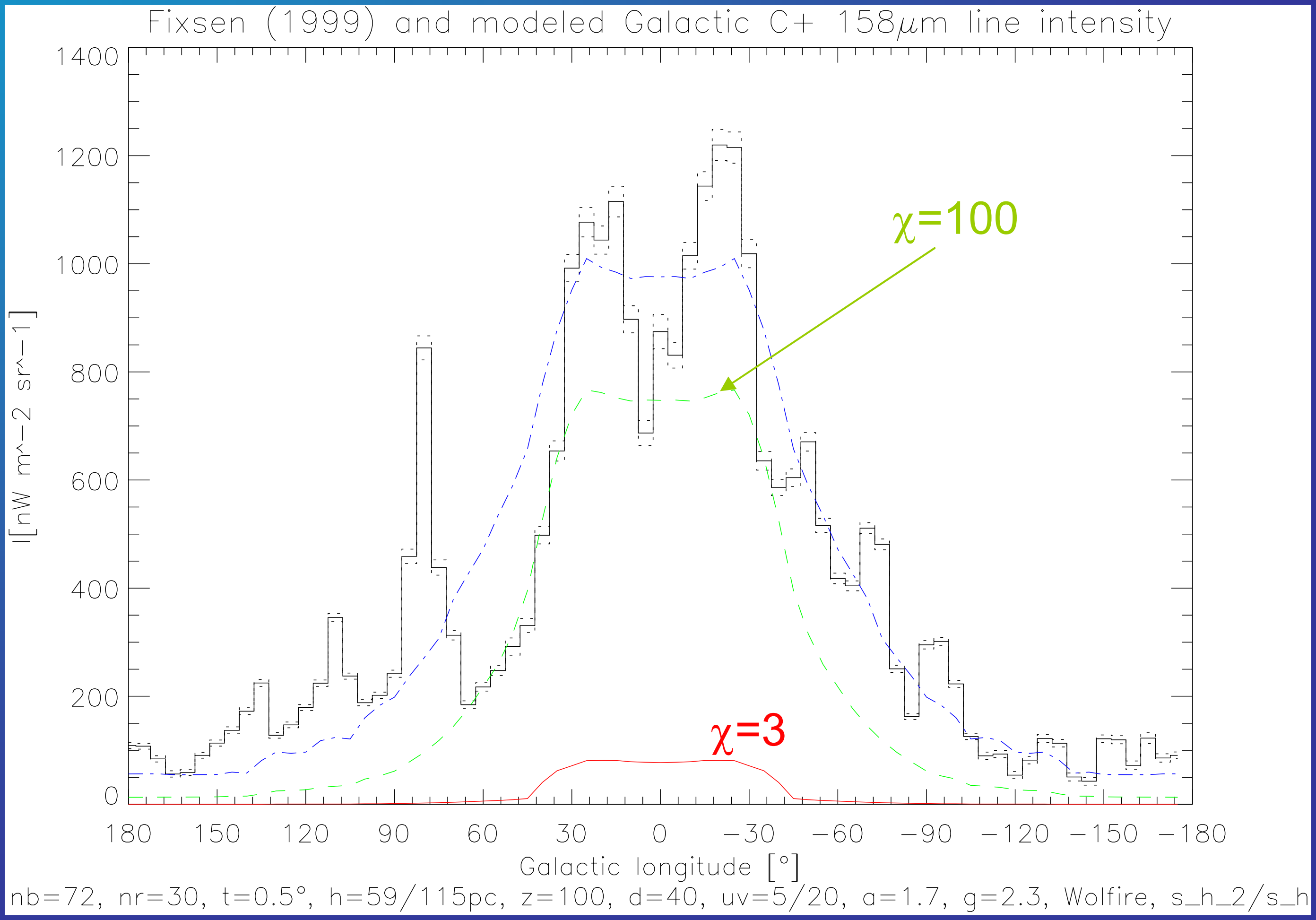
•Summary

Modeling the MW



- Introduction
- The KOSMA-τ Code
- Low Z PDRs
- [CII]/CO(1-0)
- [CI]/CO(1-0)
- Clumpy PDRs
- Modeling the MW
- Summary

Modeling the MW



Summary

- KOSMA-τ model, a spherical PDR code featuring isotropic FUV illumination and a highly modular chemistry
- Z-dependence of the gas temperature in PDR
- Z-dependence of the C^+-layer
- Influence of geometrical beam filling on the total surface brightness
- Observational trend in Galactic and extragalactic [CII]/CO(1-0) with metallicity observations can be explained with spherical PDR model results

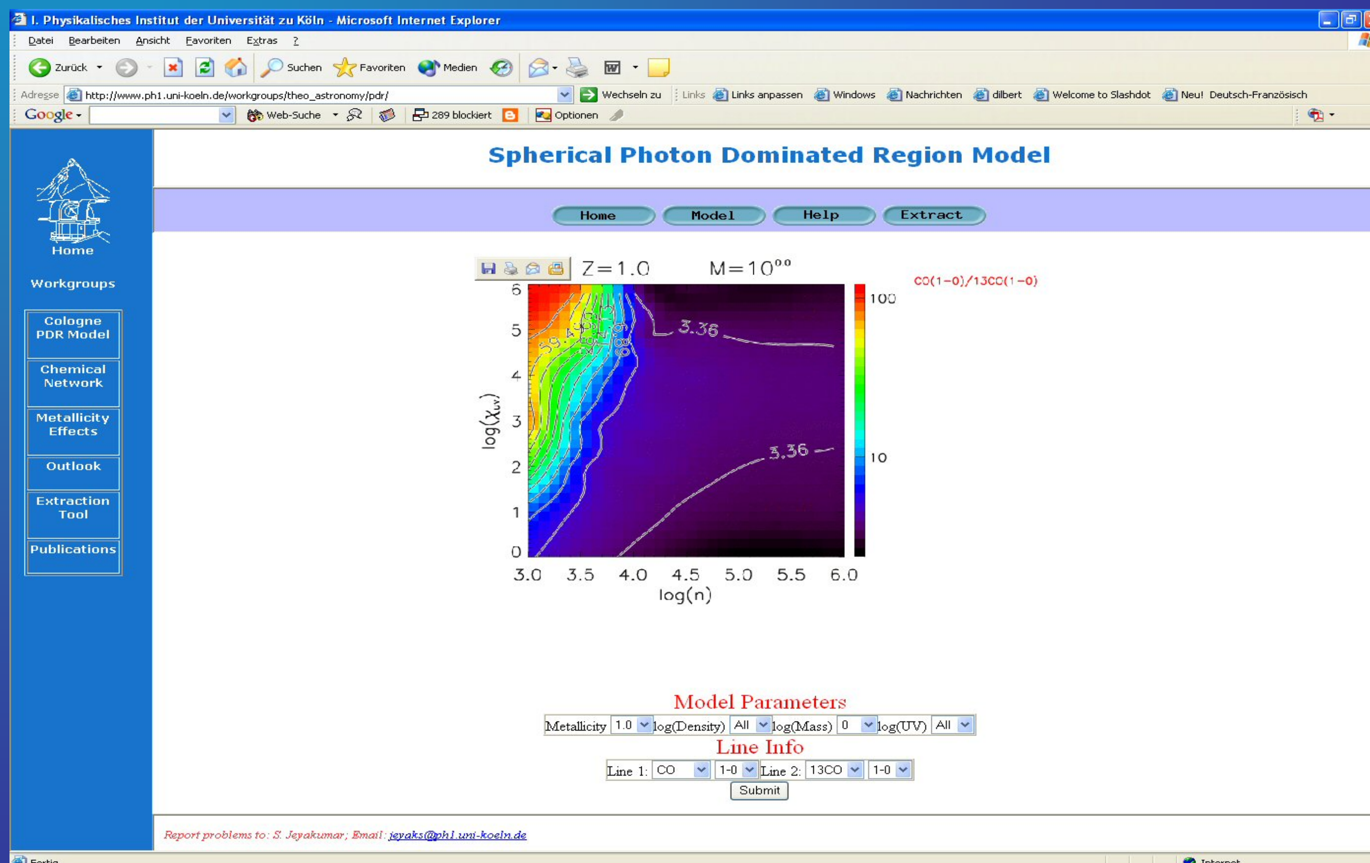
Summary

- The connection between [CI]/CO(1-0) and Z is more complicated, but again the observational trend can be reproduced
- By applying C-M spectra and M-S relations to the KOSMA-τ database it is possible to analyze large surveys, i.e. observations with large beam filling
  $\rightarrow$ application to a simple MW-model in order to explain COBE results as PDR emission ([CII] can only be explained partly)
- Clump-ensemble approach suitable for any single position observation, face-on galaxy scan, etc. with considerable beam filling.

Thank you for your attention!

- •Introduction
- •The KOSMA-τ Code
- •Low Z PDRs
- •[CII]/CO(1-0)
- •[CI]/CO(1-0)
- •Clumpy PDRs
- •Modeling the MW
- •Summary

http://www.ph1.uni-koeln.de/workgroups/theo_astronomy/pdr/



•Introduction

•The KOSMA-τ Code

•Low Z PDRs

•[CII]/CO(1-0)

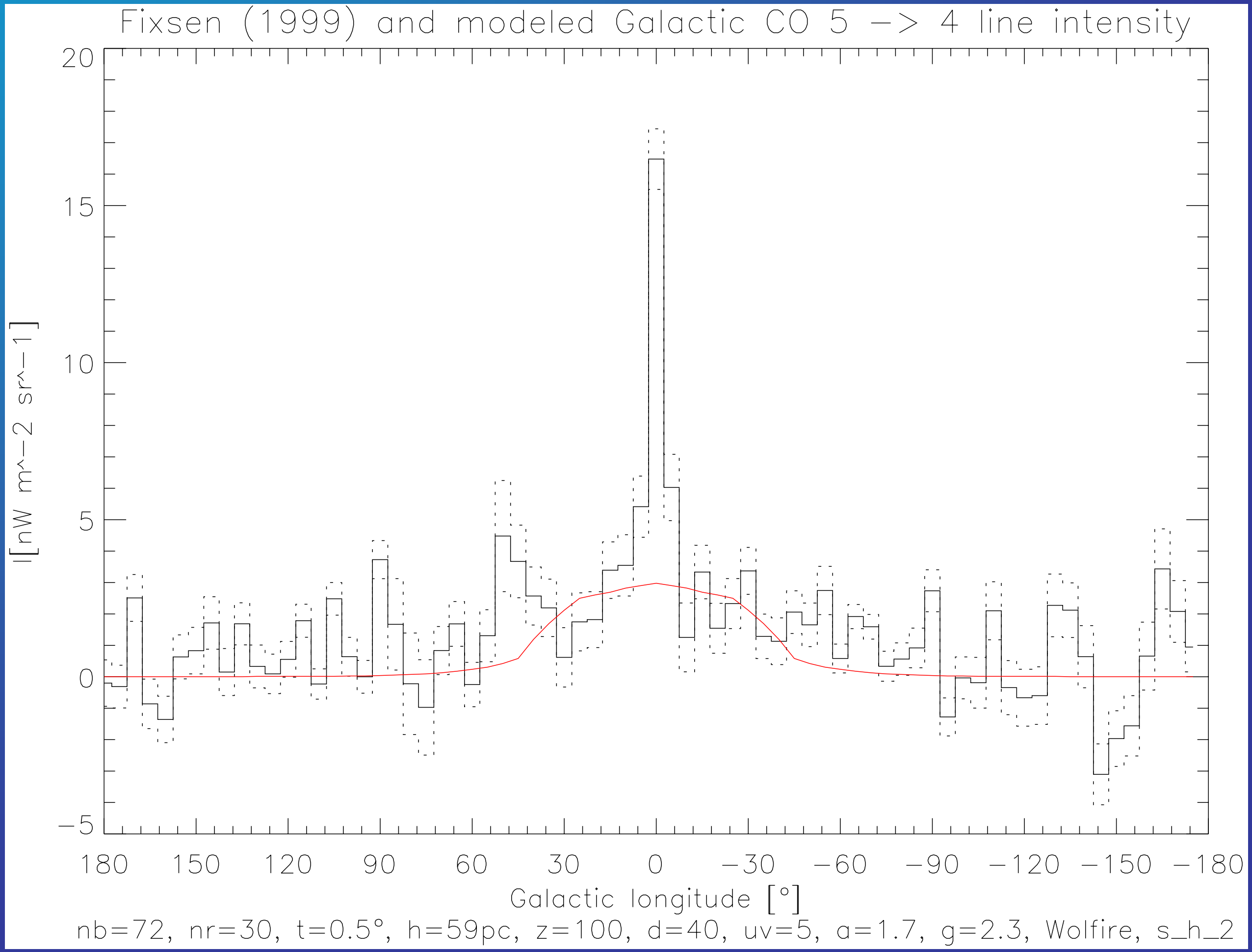
•[CI]/CO(1-0)

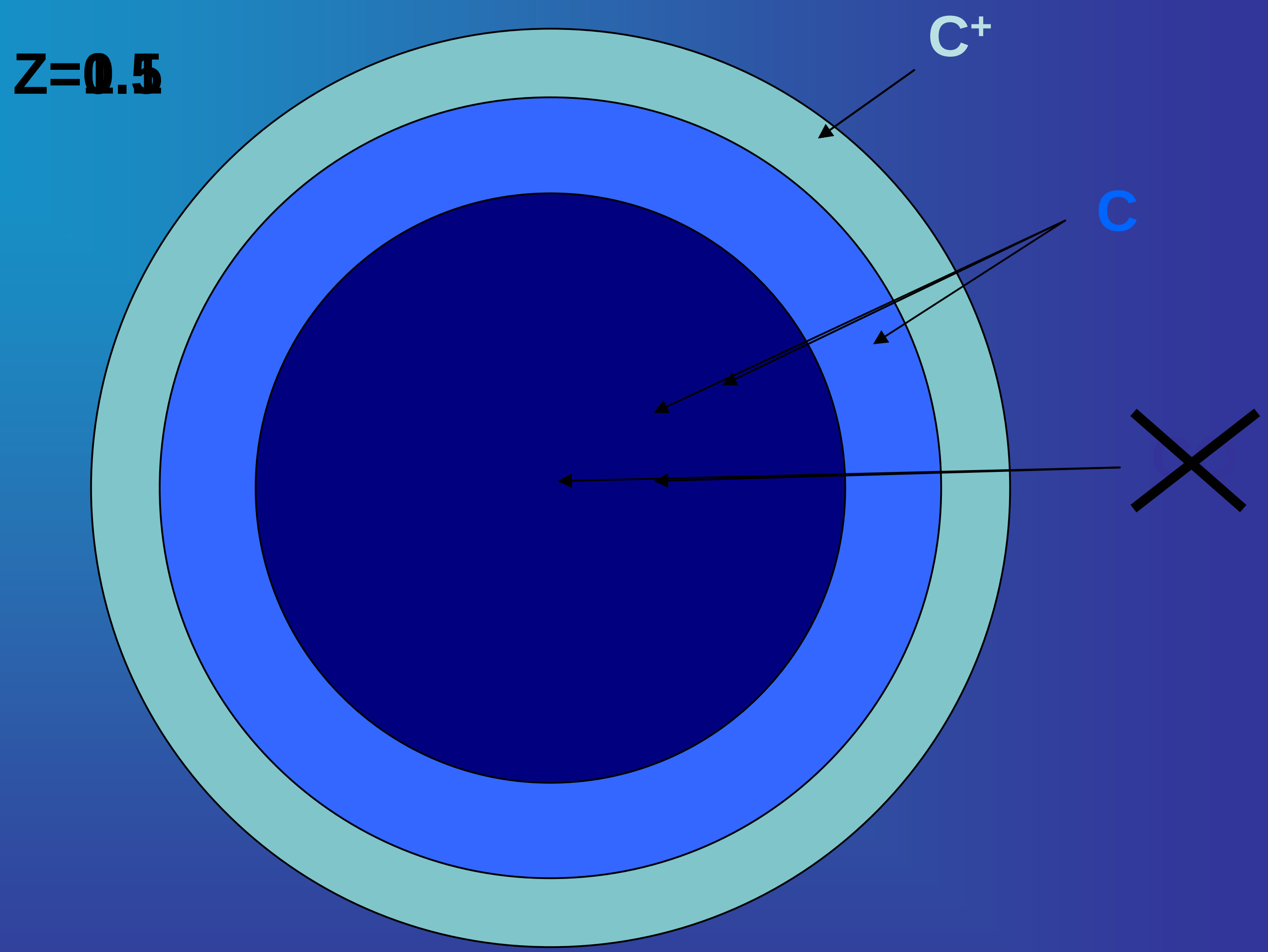
•Clumpy PDRs

•Modeling the MW

•Summary

Modeling the MW





Z=0.5
C+
C