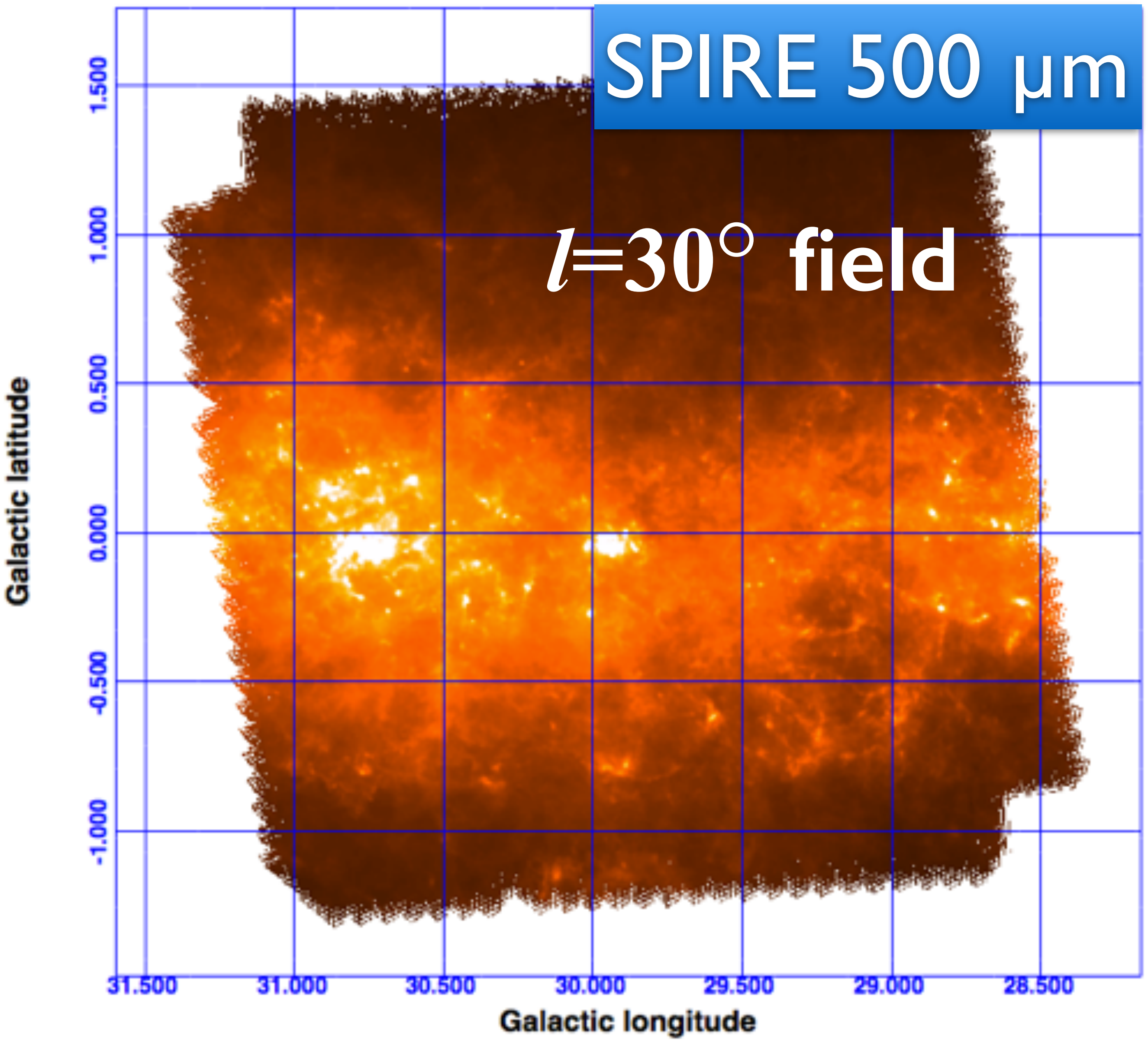
Dust in Molecular Clouds and 3D Model of the ISM

Jiali Zhu (NAOC)

Outline

- Focus and Data
  - The FIR emission from big grains
  - Hi-GAL (The Herschel infrared Galactic Plane Survey)
  - GRS (the Galactic Ring Survey): locate the molecular clouds
- Intermediate Result: Distribution of the FUV field in the Galactic plane
- The Progress of the 3D Model of the ISM
- Future Plan

Hi-GAL Project



The FIR emission is from big grains (BGs)

BGs are in temperature equilibrium

radius a ≳ 0.01 μm

domain the FIR emission at λ≳50 μm

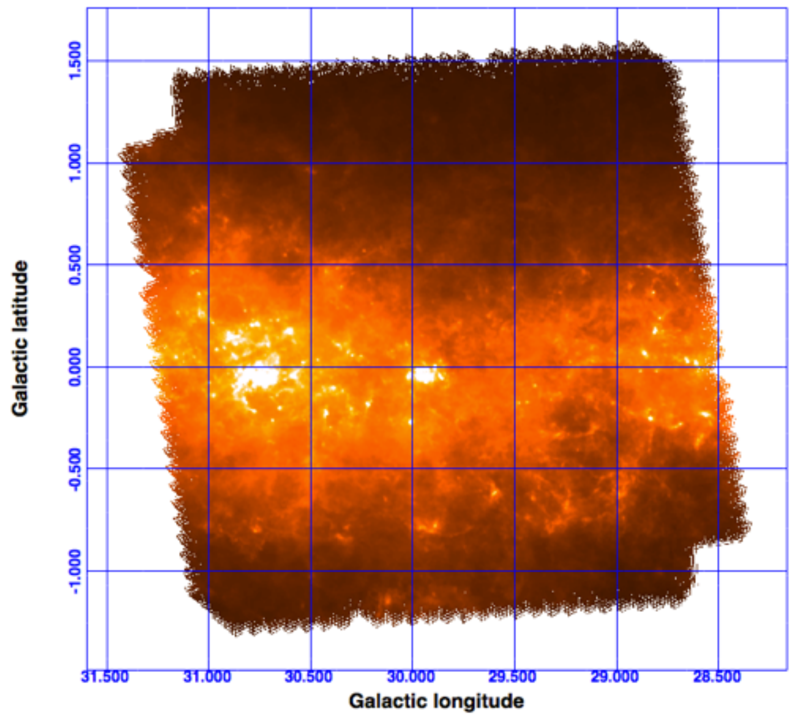
Hi-GAL: The Herschel infrared Galactic Plane Survey

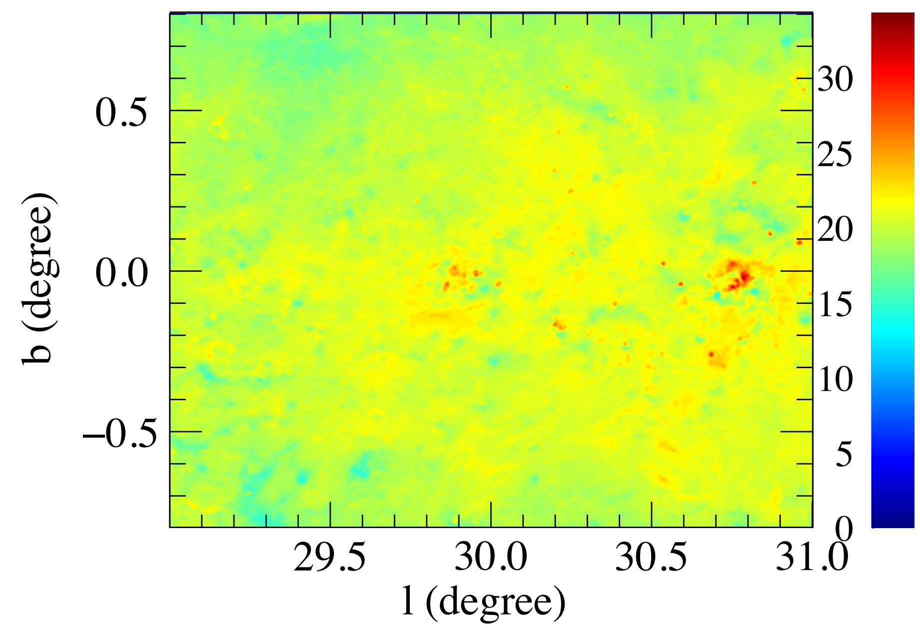
✓ 70~500 μm mapping: PACS 70, 160 μm; SPIRE 250, 350, 500 μm

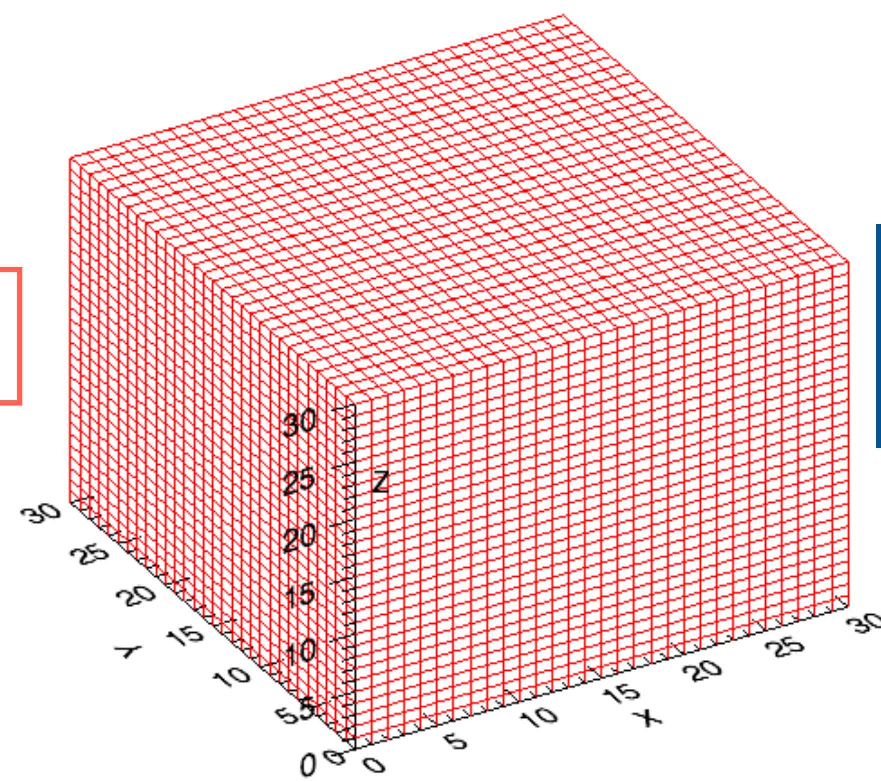
✓ Range： the whole Galactic plane， $|b|\leq 1^{o}$

From 2D to 3D

2D Observation → SED fitting → G_0 distribution





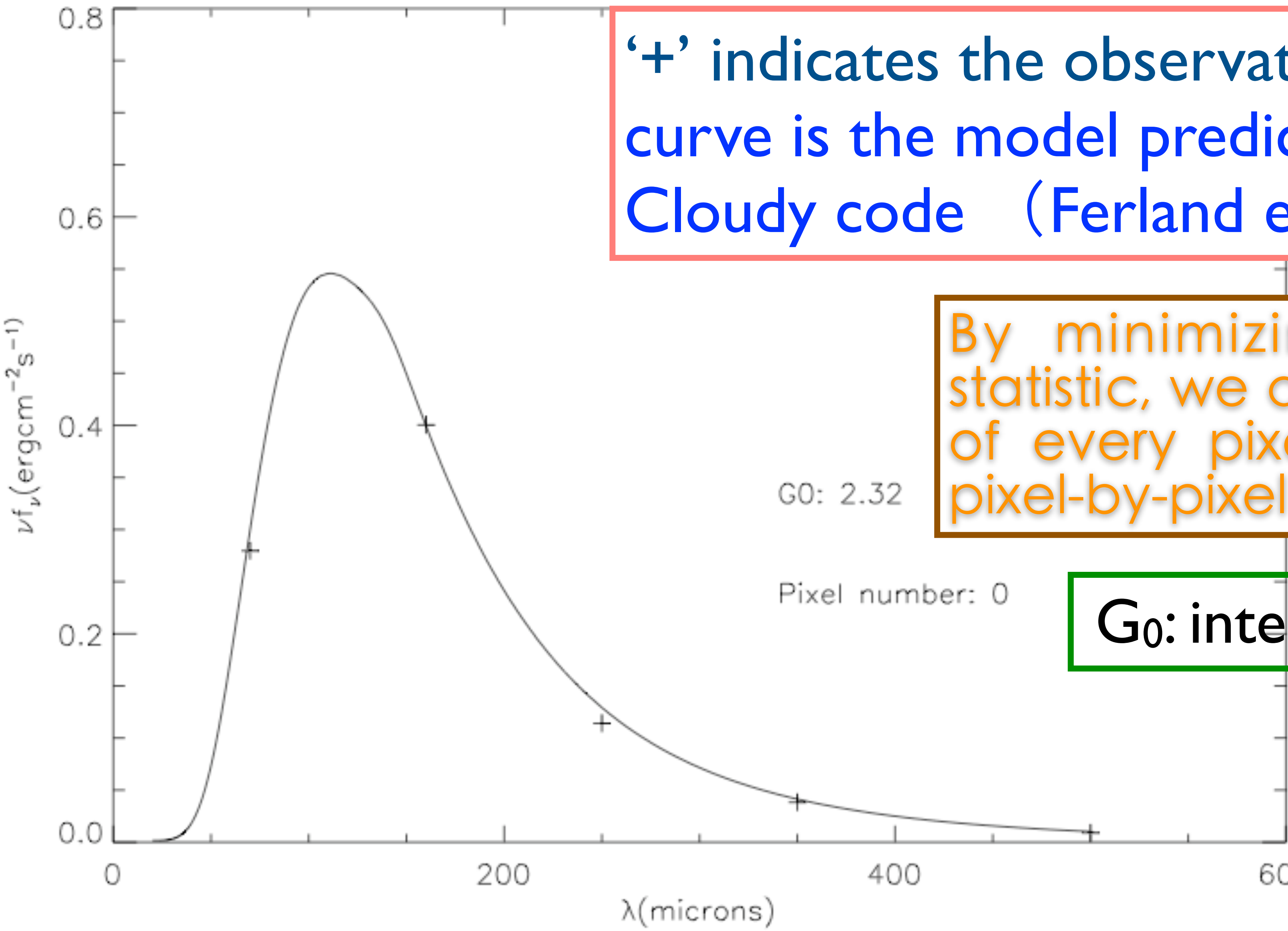


3D model of the ISM

Invert the 3D distribution of dust

Typical Example of SED Fitting: derive the G_0

Dust grains absorb FUV photons and reemite in FIR wavelength range.



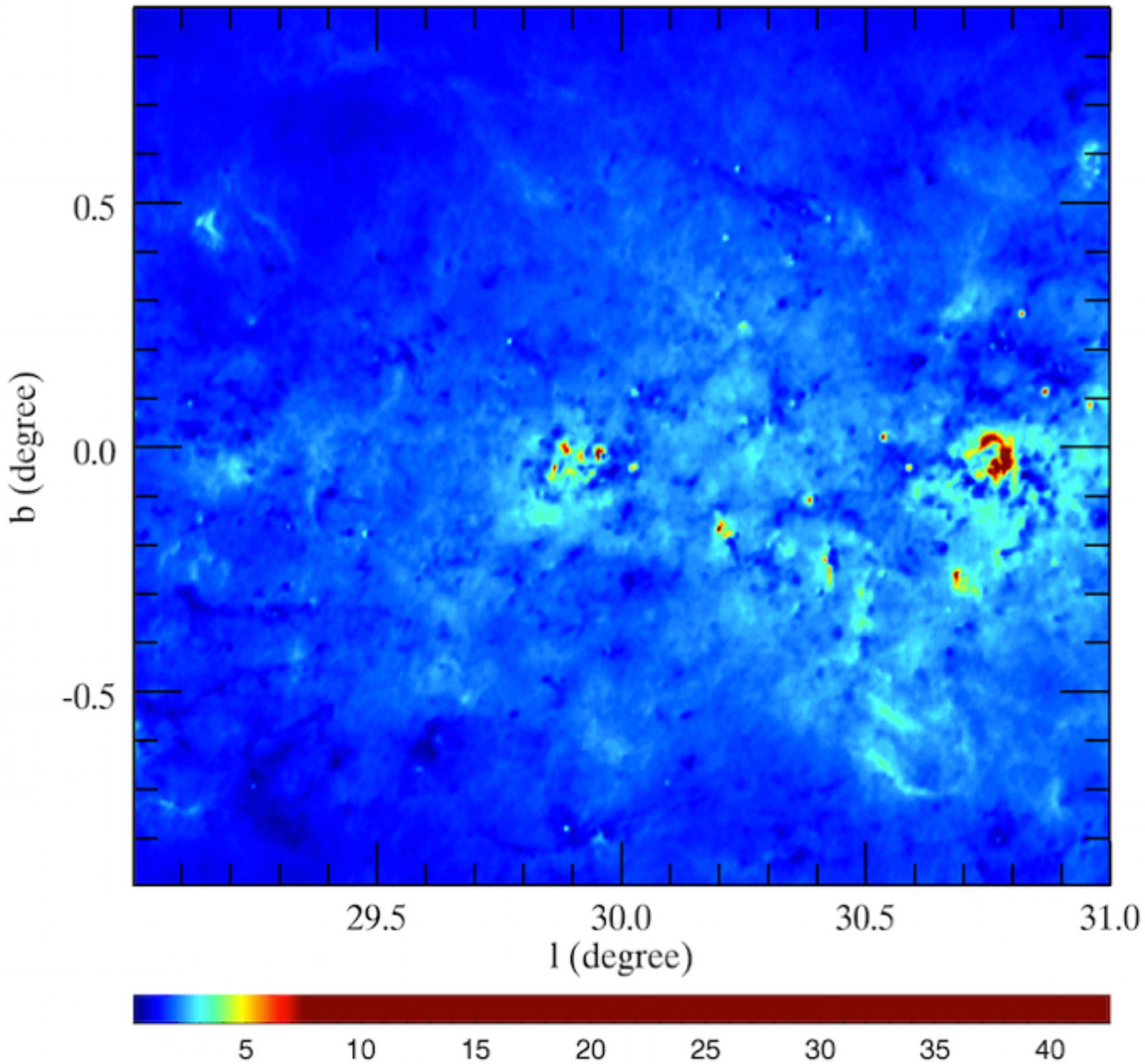
'+' indicates the observation data
curve is the model prediction calculated by Cloudy code （Ferland et al. 2013）

By minimizing the chi-square statistic, we derived the best-fit G_0 of every pixel by fitting the SED pixel-by-pixel

G_0: intensity of the FUV field

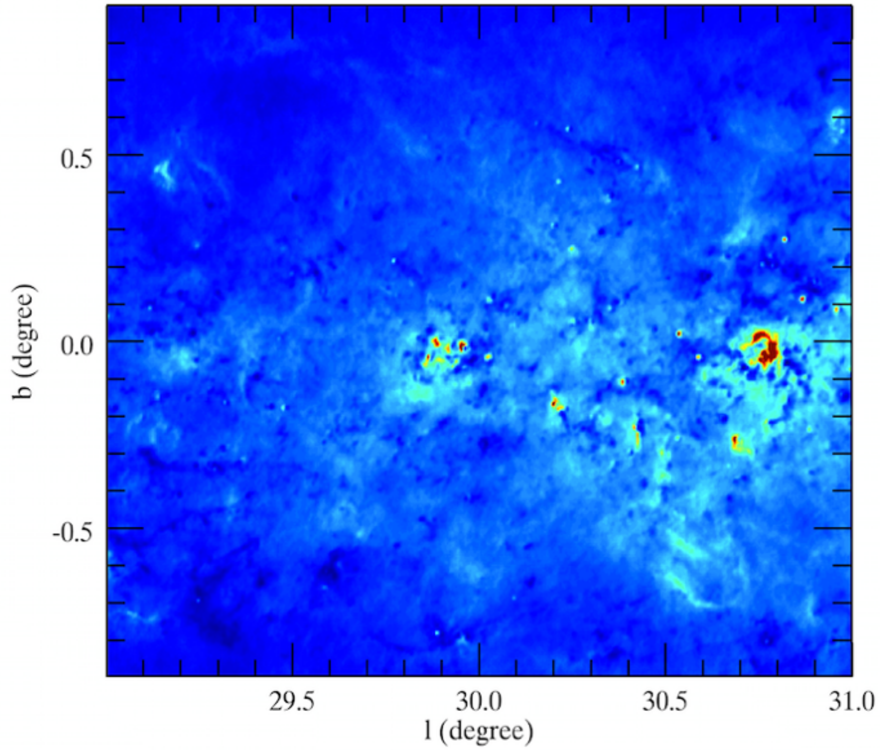
Size distribution of dust grains : $n(a) \propto a^{-3.5}$
($0.005\ \mu m < a < 0.25\ \mu m$) Mathis, Rumpl & Nordsieck (1977)

G_0 Distribution of the l=30° Field



3D Model of the ISM

Based on the G_0 Distribution of the l=30° Field



- ➡ 3D model of the ISM: Progress
- ➡ Application of GPU parallel computing technologies

H II Region Catalog (Paladini et al. 2003) in the $l = 30^\circ$ Field

名称	l(deg)	b(Jy)	R(kpc)[a]	D(kpc)[b]	d(pc)	$n_{e,6\ cm}(cm^{-3})$	T_{eff}(kK)	log U
G28.8 − 0.2	28.823	− 0.226	4.5	5.5	3.5	152.7	55	-2.1
G29.0 − 0.6	28.983	− 0.603	5.8	3.4	2.3	152.7	55	-2.1
G29.1 − 0.0	29.136	− 0.042	5.8	11.5	14.4	43.9	60	-0.6
G29.1+0.4	29.139	0.431	7.4	13.6	19	41.8	60	-1
G29.2 − 0.0	29.205	− 0.047	5.4	10.9	13.6	49.2	60	-0.4
G30.1 − 0.2	30.069	− 0.160	4.4	8.5	7.4	61.9	60	-0.3
G30.2 − 0.1	30.227	− 0.145	4.4	6.3/8.4	4.7/6.3	147.2/127.5	60	-0.3
G30.3 − 0.0	30.277	− 0.020	4.4	6.2	5	70.5	60	-1.7
G30.4 − 0.2	30.404	− 0.238	4.3	8	8.6	90.5	58	-2.25
G30.5 − 0.3	30.502	− 0.290	4.3	7.3	9.1	68.7	60	-1.65
G30.5+0.4	30.467	0.429	5.7	3.6/11	5.6/17.3	59.8/34.2	60	-2.6
G30.6 − 0.1	30.602	− 0.106	4.4	7.3	4.9	158.2	60	-1.05
G30.7 − 0.3	30.694	− 0.261	4.5	8.3	5.3	185.4	60	-1.15
G30.8 − 0.0	30.776	− 0.029	4.6	5.7	7.2	345.2	60	-1.25
G31.0+0.5	31.05	0.48	7.1	12.9	10.5	77.8	60	-2.8
G31.1+0.3	31.13	0.284	4.4	7.3	4.2	132.7	55	-2.25

Distance to the Galactic center
Distance to the solar

- Construct the radiative transfer model using Cloudy
- Compute the G_0 as a function of the column density integrated along the light path for every H II region

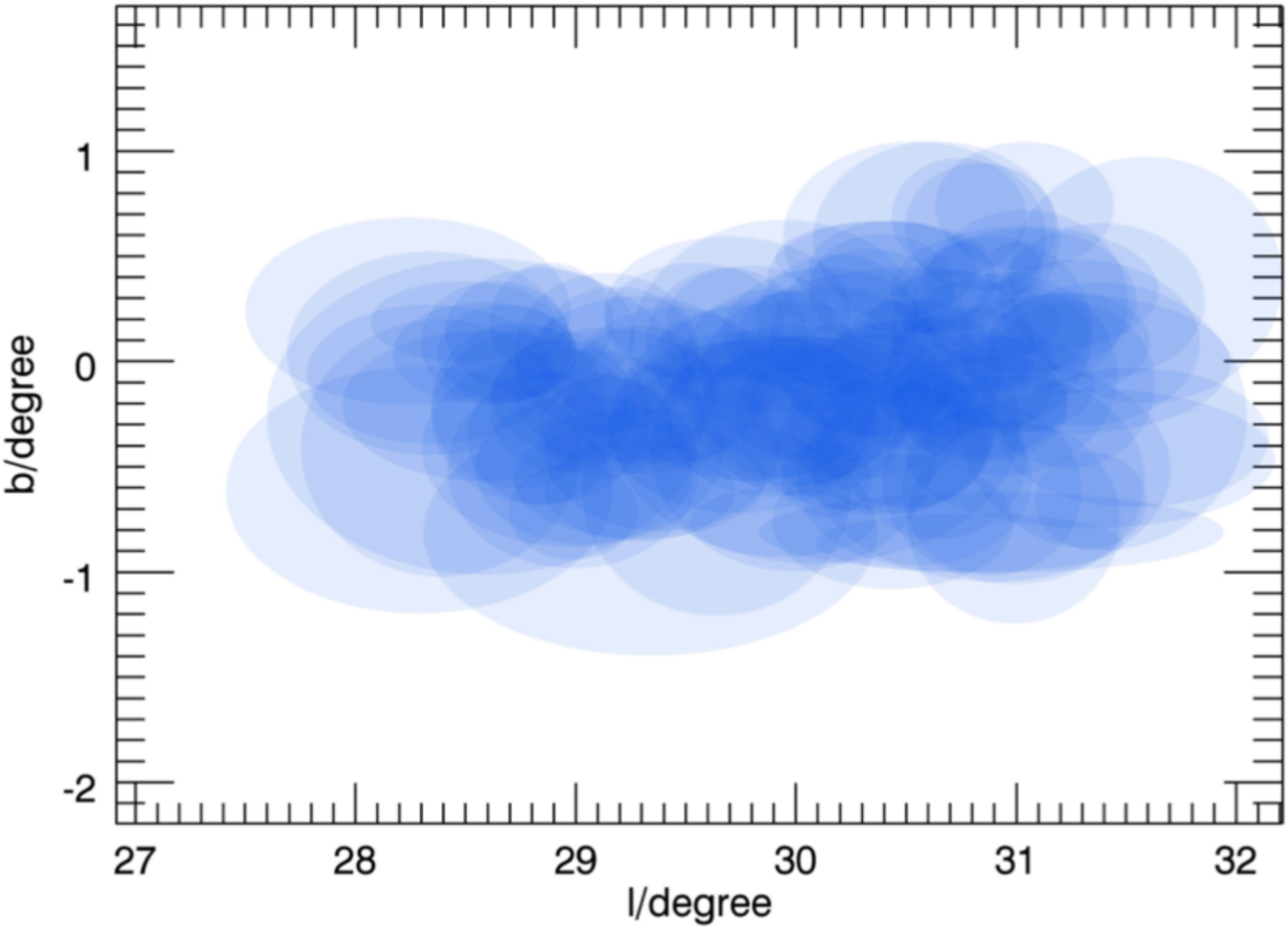
HII regions provide the radiation field in the 3D model

Part of GRS CO data

(104 clouds in total in the $l = 30^\circ$ field ,Roman-Duval et al. 2009)

Index	l(deg)	b(deg)	$\Delta l(deg)$	$\Delta b(deg)$	D(kpc)
1	29.89	-0.06	0.42	0.41	6.78
3	30.79	-0.06	0.32	0.39	6.22
5	30.44	-0.26	0.46	0.47	7.3
7	29.64	-0.61	0.61	0.60	4.85
9	28.84	-0.26	0.50	0.42	5.55
11	28.59	-0.21	0.36	0.65	5.5
13	29.94	-0.76	0.42	0.17	5.35
15	29.14	-0.31	0.30	0.24	6.03
17	29.54	0.19	0.41	0.28	5.07
19	31.29	0.09	0.55	0.39	7.25
21	30.69	0.04	0.39	0.39	5.1
23	29.29	-0.61	0.24	0.43	4.2

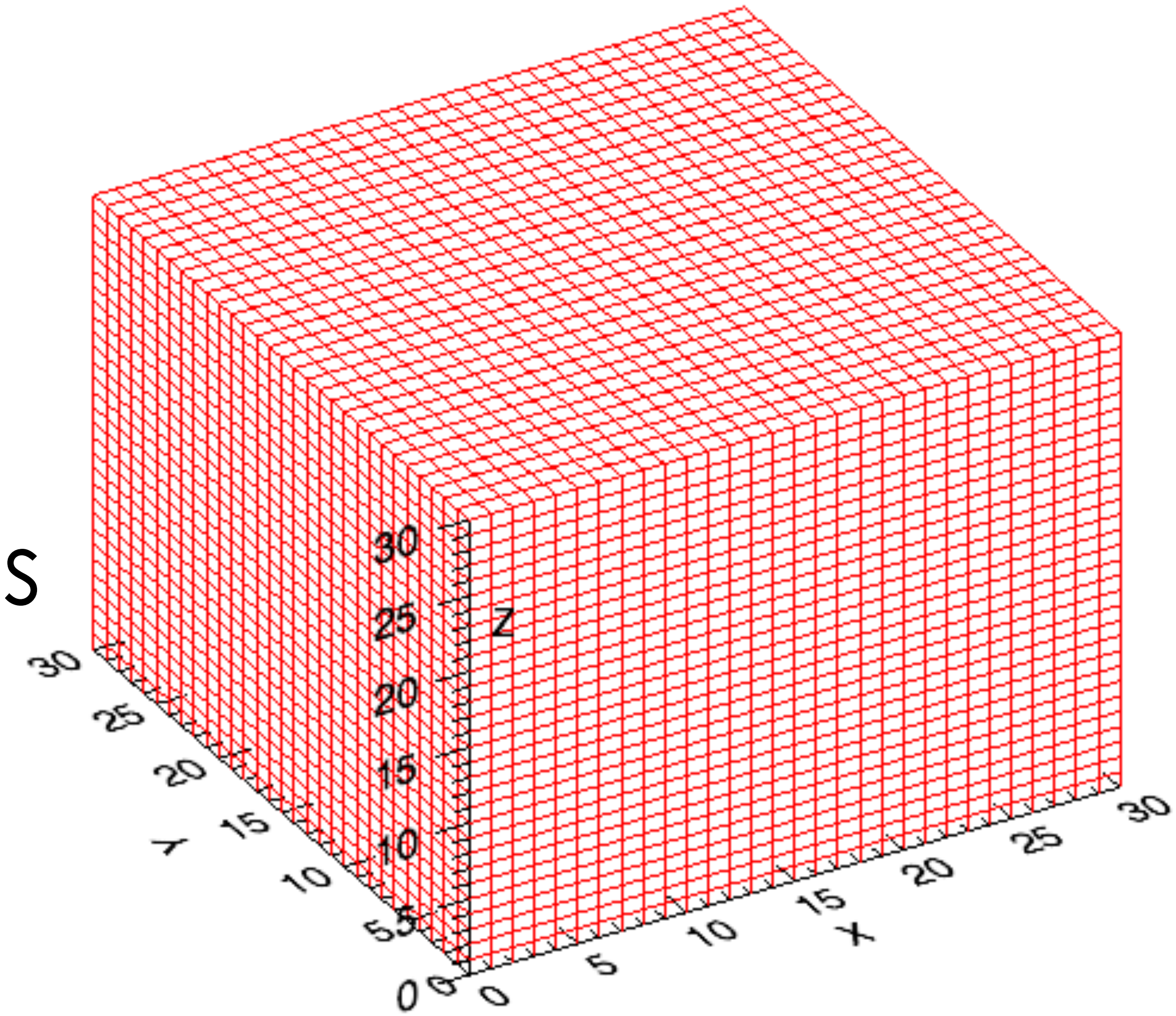
These clouds locate the dust associated with molecular clouds to reduce the computational cost



$l = 30^\circ$ field overlaid with molecular clouds (translucent ellipses)

Model Description

1. Divide the 3D space into grid cells
2. Put hot stars into cells or fill cells with gas
3. Other cells are keeping vacuum



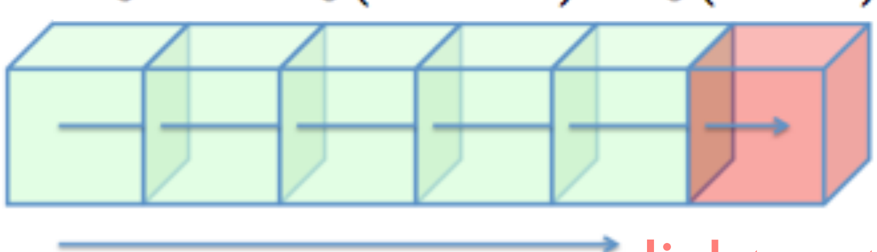
Combined with radiative transfer code and the grid geometry

Model description

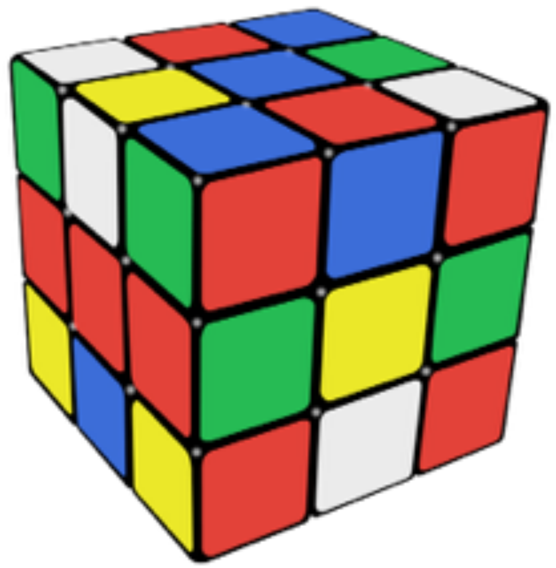
- Emission from hot stars is absorbed by cells along the light path.
- The absorption depends on the column density integrated along the light path.
- With a certain 3D distribution of the cell density, we can calculate the G_0 absorbed by every cell.

G_0 corresponding to column density is pre-calculated by Cloudy

$$G_0 = G_0(\text{before})\text{-}G_0(\text{after})$$



- The absorption is then projected to the Galactic Plane to derive a 2D simulated G_0 map, which varies with the 3D distribution of cell density.



A 3D space with a certain density distribution

We compare the simulated map with the one derived by SED fitting, to find the upper-limit for absorption of dust associated with molecular clouds.

- The best fit values of density distribution will minimize the difference between the simulated G_0 map and the "observed" G_0 map.

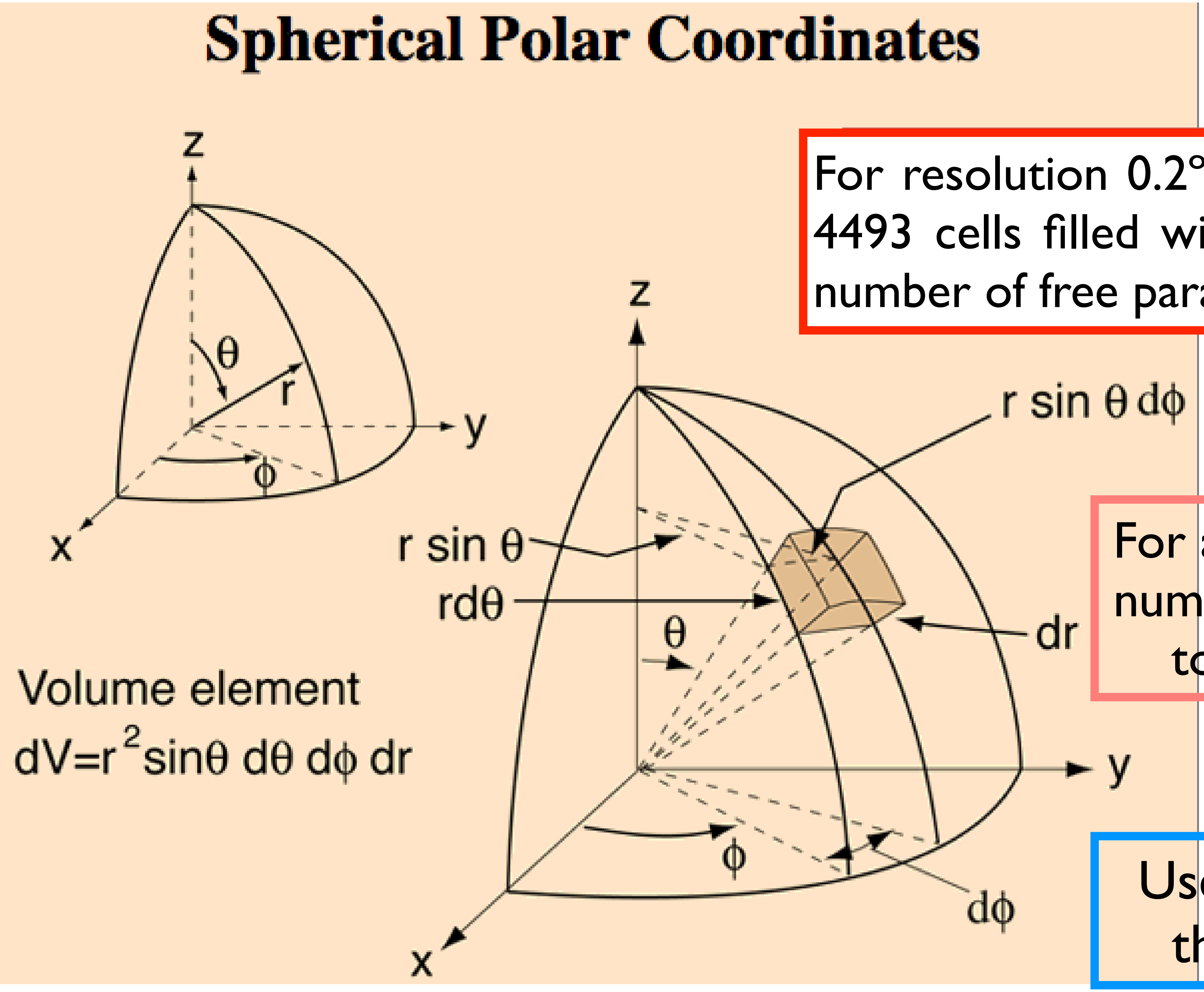
Preliminary Results

Progress： **by comparing model predication with observations, we derive the portion of FUV emission absorbed by dust grains associated with molecular clouds in the l=30° field at a low grid resolution**

Ultimate goal： automatically invert the 3D distribution of the ISM properties in the Galactic plane

from small scale (local) to large scale (global)

significant computational cost in the fitting procedures



Grid cells: 27×151×14

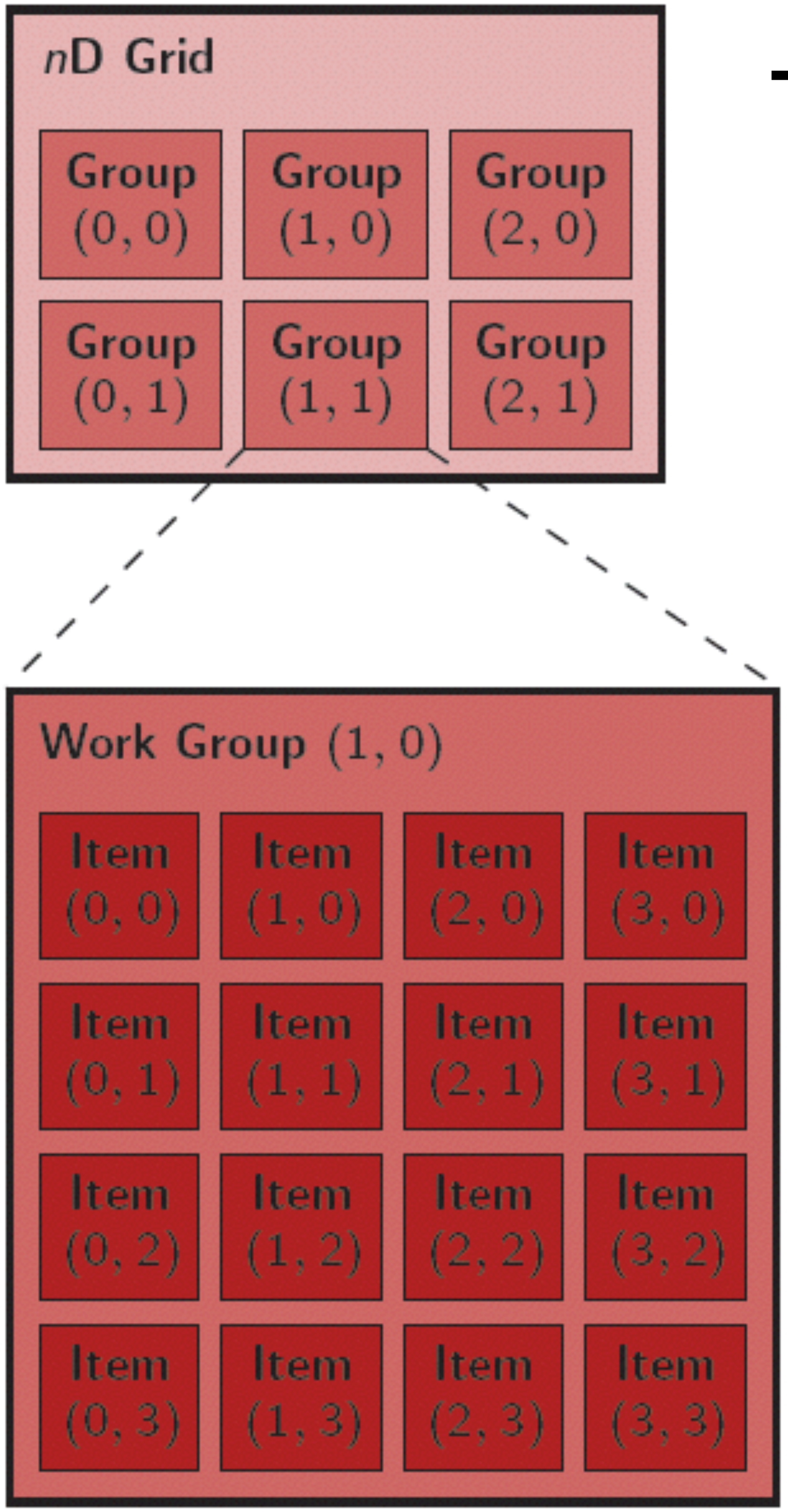
For resolution 0.2°×100 pc×0.2°, there are 4493 cells filled with gas and dust, i.e. the number of free parameter is 4493.

For a dynamic range 10, the number of possibilities is 10 to the power of 4493.

Use MCMC to perform the fitting procedure

CPU (Xeon E5620, one core)， costing ~7 min for a single calculation

GPU Parallel Computing Technologies



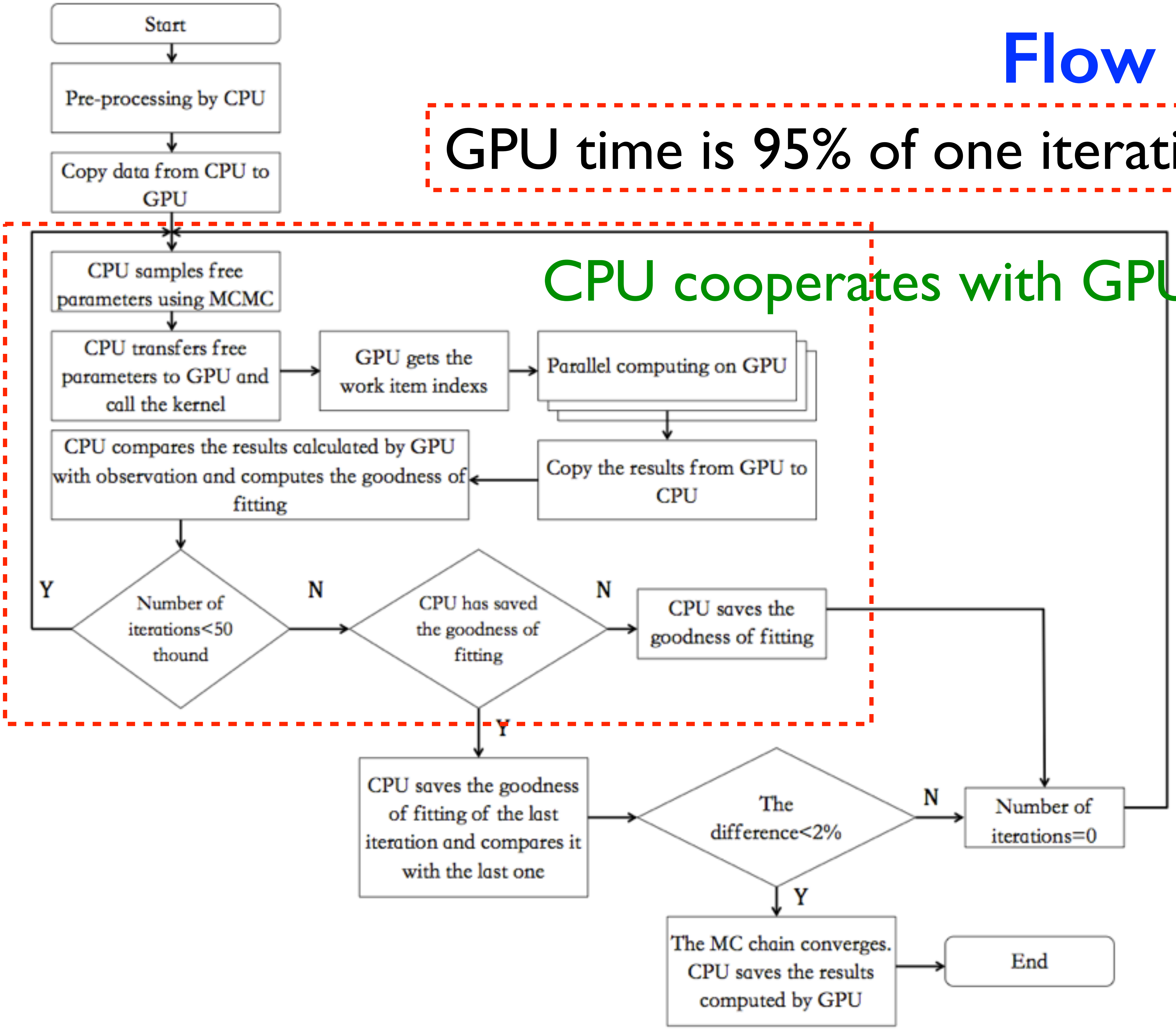
To speed up the fitting procedure

- The G_0 absorption of 4493 cells are computed in parallel on GPU
- We use OpenCL to call the GPU
- One work item of GPU corresponds to one cell

Flow Chart

GPU time is 95% of one iteration time

CPU cooperates with GPU



The computing performance of CPU and GPU

Platform	Time cost of one iteration (t/s)	Speedup
CPU(Xeon E5620, one core)	410	9535
GPU(NVIDIA C2075)	0.043	

GPU reduces the runtime significantly

TECHNICAL SPECIFICATIONS

OF CUDA CORES
> 448

FREQUENCY OF CUDA CORES
> 1.15 GHz

DOUBLE PRECISION FLOATING POINT PERFORMANCE (PEAK)
> 515 Gflops

SINGLE PRECISION FLOATING POINT PERFORMANCE (PEAK)
> 1.03 Tflops

TOTAL DEDICATED MEMORY
> 6GB GDDR5*

MEMORY SPEED
> 1.5 GHz

MEMORY INTERFACE
> 384-bit

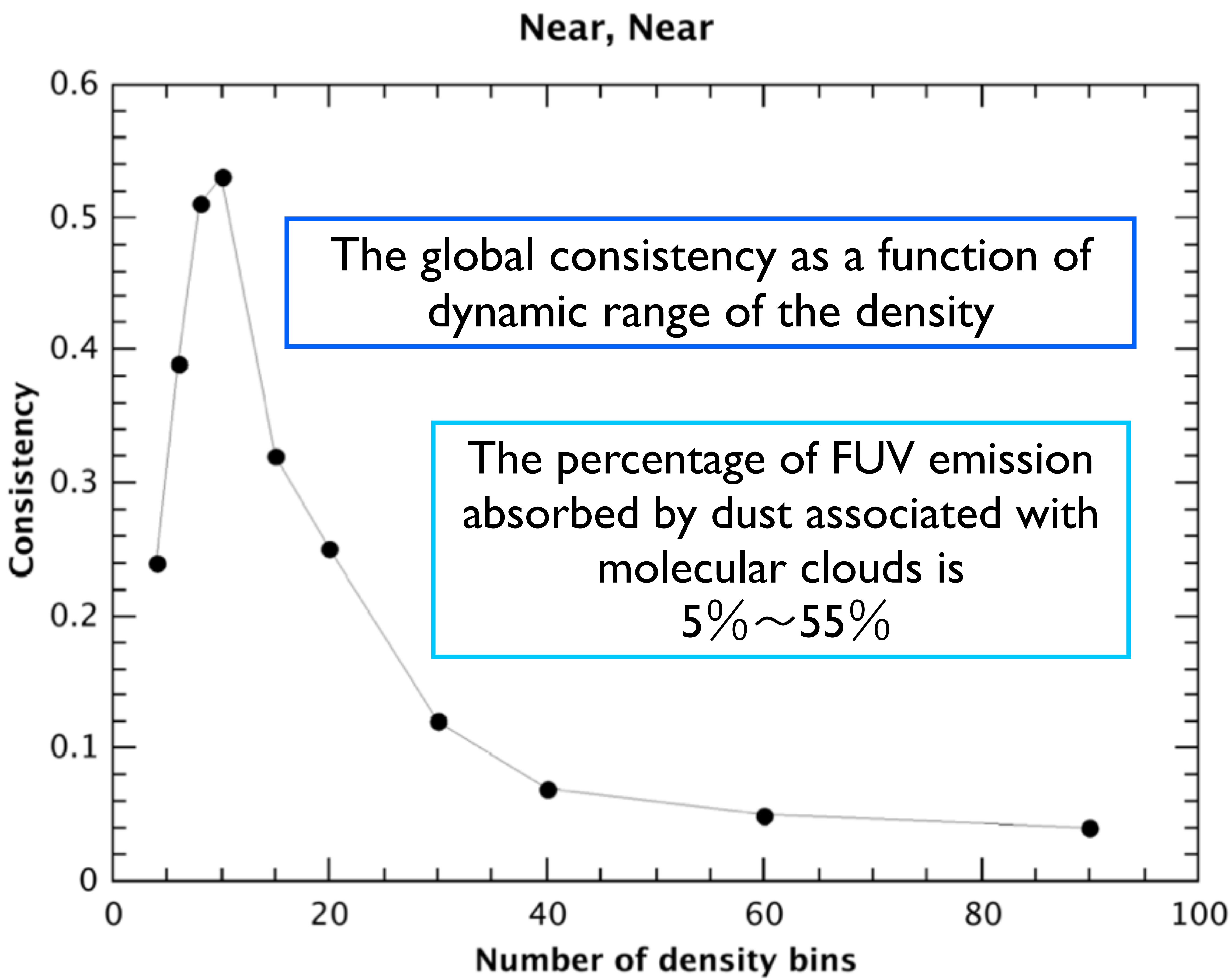
MEMORY BANDWIDTH
> 144 GB/sec

Preliminary Fitting Results

Index	$G_{0,\mathrm{model}}$	Standard Deviation	G_0	1σ error	Criterion
1	6.81	0.18	2.06	0.88	5.3
2	4.21	0.09	1.64	0.31	8.1
3	4.08	0.05	2.03	0.27	7.5
4	3.53	0.07	2.08	0.28	5.1
5	3.55	0.08	2.23	0.29	4.4

Criterion $= \frac{|G_{0,\mathrm{model}} - G_0|}{\sqrt{\delta G_{0,\mathrm{model}}^2 + \delta G_0^2}} \leq 1$ → **The FUV emission at line of sight is absorbed by the dust associated with molecular clouds**

The portion of cells with criterion≤1 → **global consistency**



The global consistency as a function of dynamic range of the density

The percentage of FUV emission absorbed by dust associated with molecular clouds is
5%～55%

Future Plan

1. **Upgrade the radiative transfer model**
   - ✓ use a 3D radiative transfer model to calculate the dust emission directly
   - ✓ no need to calculate the G_0 distribution
2. **Improve the resolution of 3D model**
3. **Include more sources, not only HII regions**

This model is under continuous development

Your suggestions and comments are welcome