CLUMPY

[1st release]

(v2011.09_corr3)

Gamma-rays signals from dark matter structures

http://lpsc.in2p3.fr/clumpy

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Comp. Phys. Comm., 183, 656 (2012) – arXiv:1201.472

V2 (in prep.): Jeans analysis, triaxiality, etc.
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1. General Considerations

2. Code Description

3. Examples

Gamma-ray flux from DM annihilation

The γ-ray flux is given by

$$\frac{d\Phi}{dE}(E,\phi,\theta,\Delta\Omega) = \frac{d\Phi^{\rm pp}}{dE}(E) \times \Phi^{\rm astro}(\phi,\theta,\Delta\Omega)$$

Particle physics

Astrophysics

Weakly Interacting Massive Particles

$$\frac{d\Phi^{\rm pp}}{dE} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m^2_{\rm WIMP}} \cdot \sum_f \frac{dN^f}{dE} B_f$$

$$\text{J} \equiv \Phi^{\rm astro} = \int_{\Delta\Omega}\int_0^{l_{\rm max}} \rho^2(l,\Omega)\, dl\, d\Omega$$

Detection or non-detection
→ Need $\Phi^{\rm astro}$ to put any constraints on DM candidate

Gamma-ray flux from DM decay

The γ-ray flux is given by

$$\frac{d\Phi}{dE}(E,\phi,\theta,\Delta\Omega) = \frac{d\Phi^{\rm pp}}{dE}(E) \times \Phi^{\rm astro}(\phi,\theta,\Delta\Omega)$$

Particle physics

Astrophysics

Weakly Interacting Massive Particles

$$\frac{d\Phi^{PP}}{dE} = \frac{2}{4\pi}\frac{\Gamma}{m^2_{\rm WIMP}}\delta\left(1-\frac{2E}{m_{\rm WIMP}}\right) \qquad D \equiv \Phi^{\rm astro} = \int_{\Delta\Omega}\int_0^{l_{\rm max}} \rho(l,\Omega)\,dl\,d\Omega$$

Detection or non-detection
→ Need $\Phi^{\rm astro}$ to put any constraints on DM candidate

Why a CLUMPY code ?

N-body simulations have limitations:

- No baryons (rapidly changing)
- 'Poor' mass resolution
- Computational requirements + speed
- Each provides one answer and they do not (always) agree

→ But they are so far what we have best as 'global' DM density estimators

Observations of galaxy, dSph galaxies and/or galaxy clusters:

- Stellar dynamics, weak lensing → start to have data-driven DM profiles
- They do not agree (nor disagree) with simulations (huge uncertainties)

Want a code that calculates Φ^{astro} and/or generates synthetic skymaps

→ Quickly
→ For any set of DM distribution parameters (smooth + clumps)
→ For any type of DM halo (MW or 'external' halo)

+ User-friendliness, modularity

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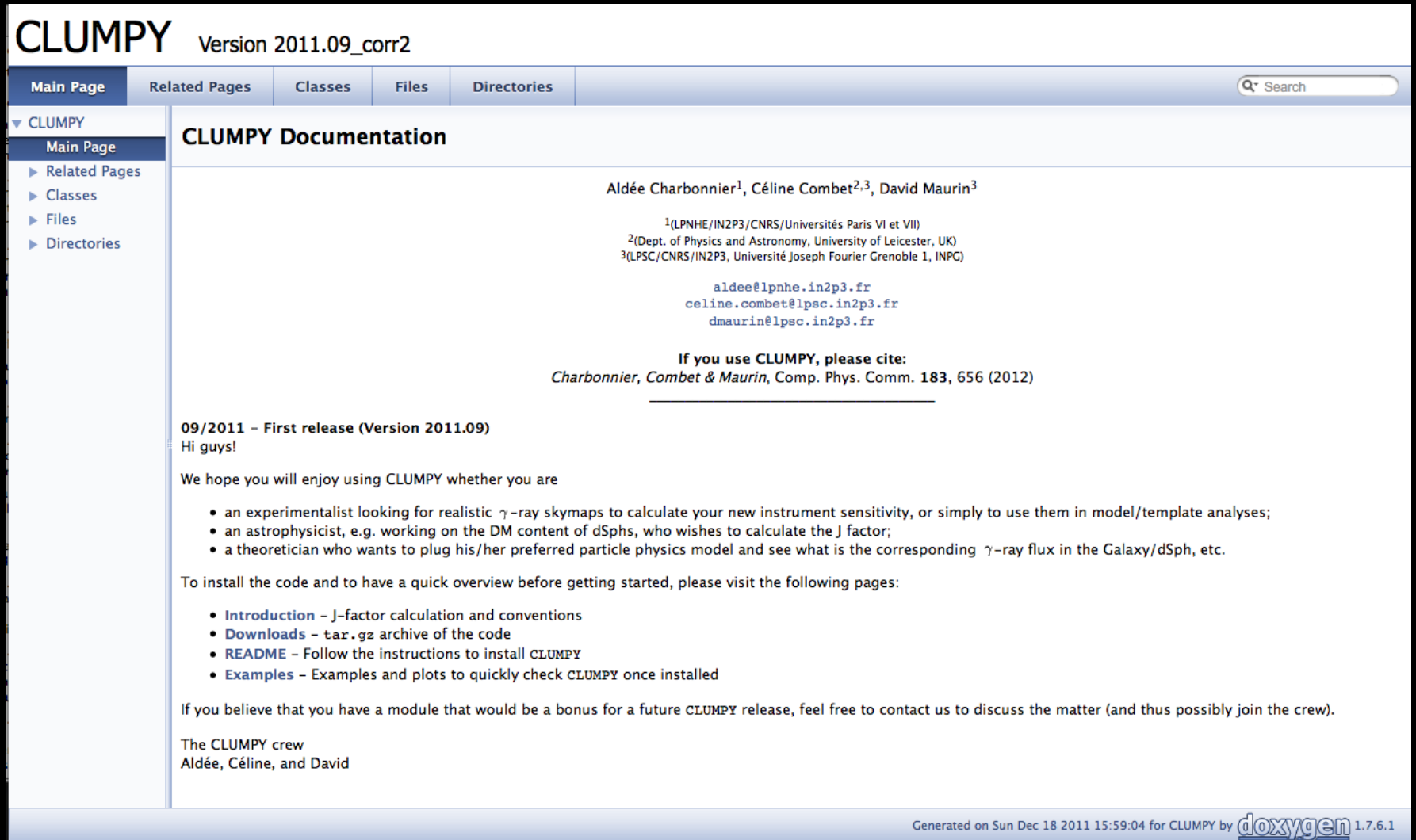
CLUMPY - Overview

- C/C++, interfaced with ROOT CERN library (+ pop-up graphics)
- Extensively documented, using Doxygen
- Documentation + Download : `http://lpsc.in2p3.fr/clumpy`



CLUMPY Version 2011.09_corr2

Main Page | Related Pages | Classes | Files | Directories | Search

- CLUMPY
  - Main Page
  - Related Pages
  - Classes
  - Files
  - Directories

CLUMPY Documentation

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If you use CLUMPY, please cite:
Charbonnier, Combet & Maurin, Comp. Phys. Comm. **183**, 656 (2012)

09/2011 – First release (Version 2011.09)
Hi guys!

We hope you will enjoy using CLUMPY whether you are

- an experimentalist looking for realistic γ-ray skymaps to calculate your new instrument sensitivity, or simply to use them in model/template analyses;
- an astrophysicist, e.g. working on the DM content of dSphs, who wishes to calculate the J factor;
- a theoretician who wants to plug his/her preferred particle physics model and see what is the corresponding γ-ray flux in the Galaxy/dSph, etc.

To install the code and to have a quick overview before getting started, please visit the following pages:

- **Introduction** – J-factor calculation and conventions
- **Downloads** – `tar.gz` archive of the code
- **README** – Follow the instructions to install `CLUMPY`
- **Examples** – Examples and plots to quickly check `CLUMPY` once installed

If you believe that you have a module that would be a bonus for a future `CLUMPY` release, feel free to contact us to discuss the matter (and thus possibly join the crew).

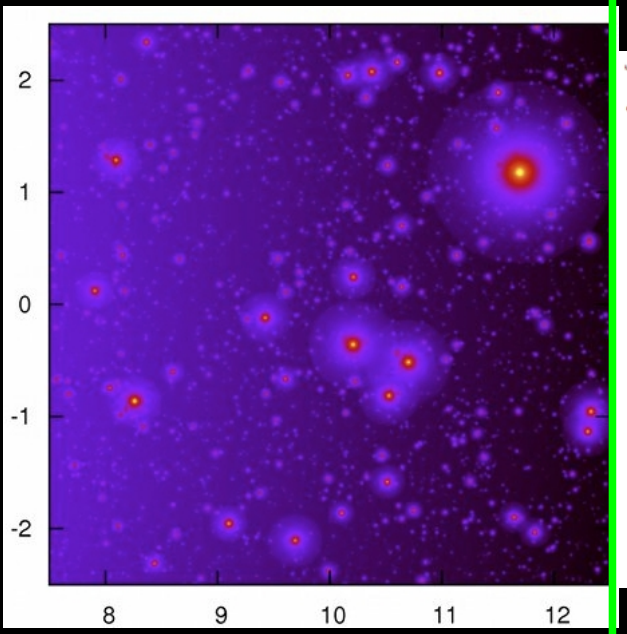
The CLUMPY crew
Aldée, Céline, and David

Generated on Sun Dec 18 2011 15:59:04 for CLUMPY by doxygen 1.7.6.1

3 main options - illustration

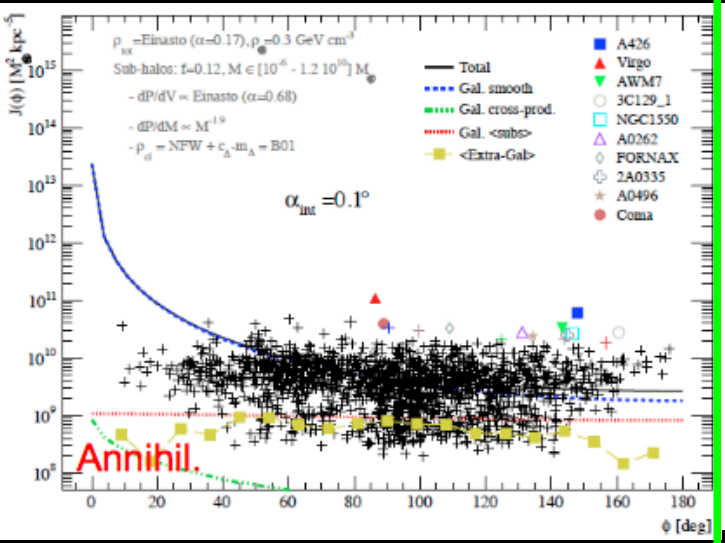
```
[combet@MacBook-Pro-de-Celine ~/RECHERCHE/CLUMPS/CLUMPY_v2011.09.CPC_corr2]$./bin/clumpy
 usage:
    ./bin/clumpy -g  => run for the Galactic halo + list of halos [optional]
    ./bin/clumpy -h  => run on (a list of) halos (not the Gal. halo)
    ./bin/clumpy -s  => run on statistical-hike file (or on a list of files)

N.B.: Default output is both displays and print (on screen and in file)
  => use option -d for displays only (e.g., -gd, or -hd or -sd)
  => use option -p for print only (e.g., -gp or -hp or -sp)
```

clumpy -gX



e.g., J-sky from user Galactic parameters

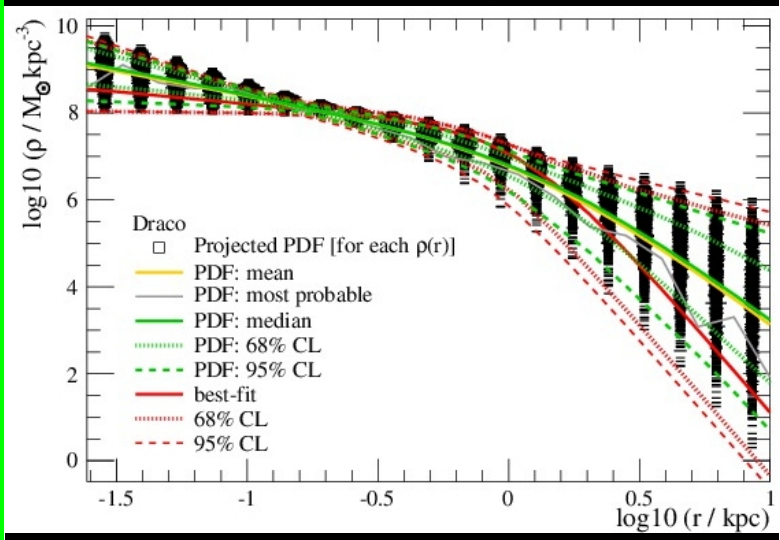
clumpy -hX



1743 galaxy clusters from MCXC catalogue

ArXiv:1203.1165

clumpy -sX



Statistics for Draco dSph DM profile

arXiV:1104.0412

3 main options - illustration

```
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```

And sub-options...

```
[combet@MacBook-Pro-de-Celine ~/RECHERCHE/CLUMPS/CLUMPY_v2011.09.CPC_corr2]$./bin/clumpy -g
  usage:
   [rho_sm+<sub>(r)          ]  ./bin/clumpy -g1  param_file  rmin[kpc] rmax[kpc] n is_log
   [Jsm+<sub>(alpha_int)     ]  ./bin/clumpy -g2  param_file  amin[deg] amax[deg] n is_log  psi_obs[deg] theta_obs[deg]
   [Jsm+<sub>(theta)         ]  ./bin/clumpy -g3  param_file  tmin[deg] tmax[deg] n is_log
   [Jsm+<sub>+list(theta)    ]  ./bin/clumpy -g4  param_file  tmin[deg] tmax[deg] n is_log
   [2D-skymap Jsm+<sub>      ]  ./bin/clumpy -g5  param_file  psi_obs[deg] theta_obs[deg] psi_size[deg] theta_size[deg]
   [2D-skymap Jsm+<sub>+list]  ./bin/clumpy -g6  param_file  psi_obs[deg] theta_obs[deg] psi_size[deg] theta_size[deg] is_subs_list
   [2D-skymap Jsm+sub        ]  ./bin/clumpy -g7  param_file  psi_obs[deg] theta_obs[deg] psi_size[deg] theta_size[deg] user_rse[%]
   [2D-skymap Jsm+sub+list   ]  ./bin/clumpy -g8  param_file  psi_obs[deg] theta_obs[deg] psi_size[deg] theta_size[deg] user_rse[%] i
s_subs_list

 N.B.: to see default parameter values (examples), use "-1D", "-2D", etc.
 N.B.: default output is both displays and print (on screen and in file)
   => use option -d for displays only (e.g., -dg1)
   => use option -p for print only (e.g., -pg1)

 ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
 ++++ set gGAL_SUBS_N_INM1M2 to 0 in param_file for smooth only ++++
 ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

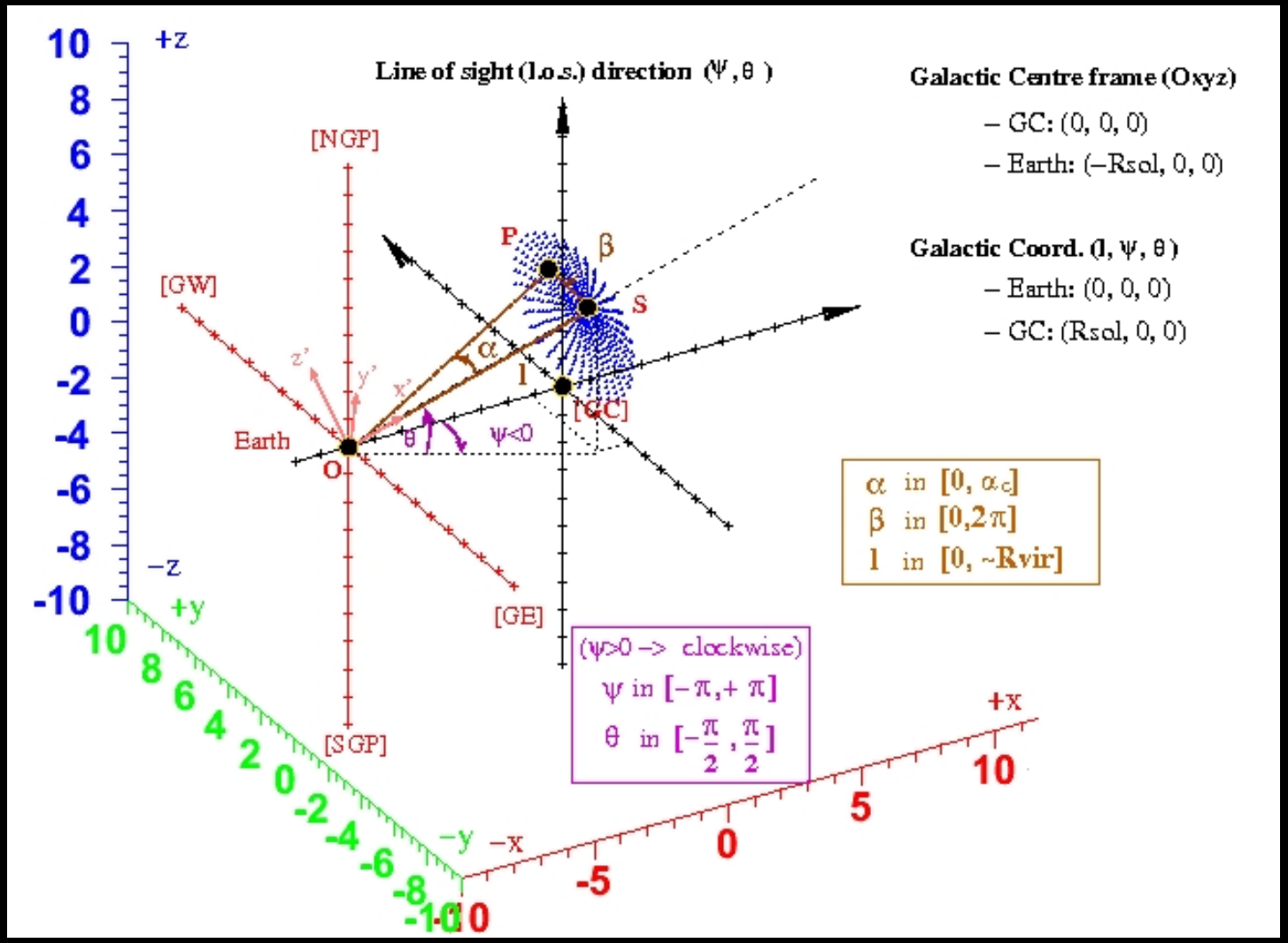
CLUMPY's libraries

include/clumps.h [code]	Clump functions: concentration, spatial and mass distribution, ...
include/geometry.h [code]	Geometric transformation from spher.Gal.coord. to Cartesian Gal.coord. (and vice-versa)
include/inlines.h [code]	Inline variables/macros (constants, conversions)
include/integr.h [code]	Integration routines (adaptive refinement for lin. and log. step)
include/integr_los.h [code]	Integrates along a l.o.s. (line of sight) any function $f(l,\Omega)$: $I_{l.o.s} \equiv \int_{\Delta\Omega}\int_{l_{min}}^{l_{max}} f(l,\Omega)\,dl d\Omega$
include/janalysis.h [code]	J-factor (Gal. w/o sub-halo mean/drawn w/o list) for annihil. $[M_\odot^2\ kpc^{-5}]$ or decay $[M_\odot\ kpc^{-2}]$
include/misc.h [code]	Miscellaneous simple functions used in several places
include/params.h [code]	Global parameters declaration/initialisation (Galaxy, DM, Cosmology, SIMU)
include/profiles.h [code]	Profile $\rho(r)$ $[M_\odot\ kpc^{-3}]$ and related functions (applicable for halos, sub-halos...)
include/spectra.h [code]	Spectra from DM annihilations: $\Phi^{PP}(E_\gamma) \equiv \frac{d\Phi_\gamma}{dE_\gamma} \equiv \frac{1}{4\pi}\frac{\langle\sigma_{ann}v\rangle}{2m_\chi^2}\cdot\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f$

All extensively described in the Documentation...

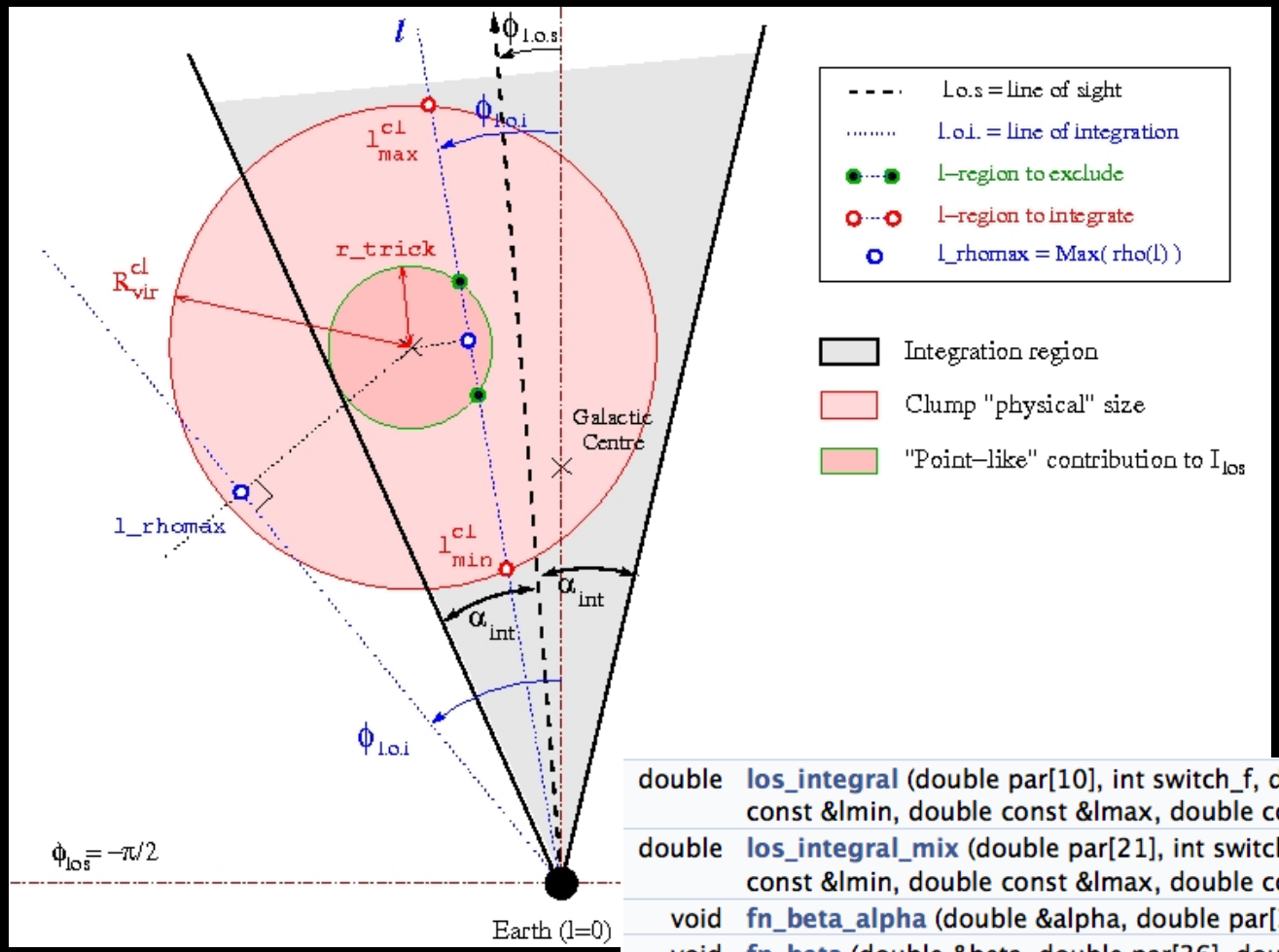
geometry.h

Contains all the changes of coordinates plus useful geometrical calculations



integr_los.h

$$F = \int_{\Delta\Omega} \int_0^{l_{\max}} f(l,\Omega)\, dl d\Omega = \int_0^{2\pi} d\beta \int_0^{\alpha_{\rm int}} \sin\alpha\, d\alpha \int_0^{l_{\max}} f(l,\alpha,\beta;\psi,\theta)\, dl d\alpha d\beta$$



Based on adaptative log-step Simpson integration (user-defined precision)

double	**los_integral** (double par[10], int switch_f, double const &psi_los, double const &theta_los, double const &lmin, double const &lmax, double const &eps, bool is_verbose=false)
double	**los_integral_mix** (double par[21], int switch_f, double const &psi_los, double const &theta_los, double const &lmin, double const &lmax, double const &eps, bool is_verbose=false)
void	**fn_beta_alpha** (double &alpha, double par[36], double &res)
void	**fn_beta** (double &beta, double par[36], double &res)
void	**integrand_l** (double &l, double par[36], double &res)

DM profiles

Generic (Zhao) profile $$\rho(r) = \frac{\rho_s}{(r/r_s)^\gamma \cdot [1 + (r/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}$$

Einasto profile $$\rho(r) = \rho_e \exp\left(-d_n \left[\left(\frac{r}{r_e}\right)^{1/n} - 1\right]\right)$$

	α	β	γ
Iso	2.	2.	0.
NFW	1.	3.	1.
Moore	1.5	3.	1.5
DMS04	1.	3.	1.2
EINASTO_N	6	–	–
EINASTO	0.17	–	–
EINASTO	0.68	–	–

Density profiles derived from simulations

$$\rho_{\rm tot}(r) = \rho_{\rm sm}(r) + \langle \rho_{\rm subs}(r) \rangle$$

where

$$\langle \rho_{\rm sub}(r) \rangle = f M_{\rm tot} \frac{dP_V(r)}{dV}$$

$$\rho_{\rm sm}(r) = \rho_{\rm tot} - \langle \rho_{\rm sub}(r) \rangle$$

Clump description

Clumps (DM substructures in the Galactic halo) are defined by:

- An inner DM profile (any from profiles.h)
- A spatial distribution
- A mass distribution

$$\frac{dN}{dV\,dM} = N_{\rm tot}\,\frac{dP_V}{dV}(\mathbf{r}) \times \frac{dP_M}{dM}(M)$$

N-body simulations (e.g. Aquarius) give :

~ 100 clumps between 10^8 **and** $10^{10} M_\odot$

$$\frac{dP_M}{dM}(M) \propto M^{-\alpha} \quad \text{with} \quad \alpha \in [1.7, 2]$$

} ~ 10^{14} clumps if $M_{\rm min} = 10^{-6} M_\odot$

$\frac{dP_V}{dV}(\mathbf{r})$ Any of the previous profiles

Number of clumps to draw

```
> ./bin/clumpy -g7 clumpy_params.txt 180. 0. 2. 2. 5
```

Skymap option

direction

map size

User-defined Tolerance [%]

```
  * find #clumps to draw below l_crit for each mass decade (2 x 2 deg map)

  mass decade  | #clumps (Gal) | l_crit (kpc) | <#clumps to draw> => #clumps = Poisson(<#clumps>)
-6.0 --> -5.0      3.536e+14      1.000e-03        1.493e-03     =>     0
-5.0 --> -4.0      4.451e+13      1.000e-03        1.879e-04     =>     0
-4.0 --> -3.0      5.604e+12      1.000e-03        2.366e-05     =>     0
-3.0 --> -2.0      7.055e+11      7.306e-03        1.161e-03     =>     0
-2.0 --> -1.0      8.882e+10      5.889e-02        7.595e-02     =>     0
-1.0 --> +0.0      1.118e+10      3.997e-01        2.849e+00     =>     3
+0.0 --> +1.0      1.408e+09      2.021e+00        3.744e+01     =>     45
+1.0 --> +2.0      1.772e+08      6.729e+00        1.047e+02     =>     117
+2.0 --> +3.0      2.231e+07      1.629e+01        8.772e+01     =>     99
+3.0 --> +4.0      2.809e+06      3.279e+01        3.662e+01     =>     44
+4.0 --> +5.0      3.536e+05      5.839e+01        1.011e+01     =>     7
+5.0 --> +6.0      4.451e+04      9.540e+01        2.175e+00     =>     1
+6.0 --> +7.0      5.604e+03      1.493e+02        4.085e-01     =>     0
+7.0 --> +8.0      7.055e+02      2.106e+02        6.663e-02     =>     0
+8.0 --> +9.0      8.882e+01      2.539e+02        9.516e-03     =>     0
+9.0 --> +10.0      1.118e+01      2.880e+02        1.251e-03     =>     0
+10.0 --> +10.1      1.984e-01      2.880e+02        2.219e-05     =>     0
```

Draw the minimum number of clumps, given user's precision requirement

CLUMPY's parameters

- 1 main file: `clumpy_params.txt`
- 1 list of objects if `clumpy -h` is chosen: `list_generic.txt`

CLUMPY's parameters

Common clump param for external haloes

Clump inner density profile

Clump mass and spatial distrib.

Calibration on N-body sims

Total Galactic density profile

clumpy -h

clumpy -g

Name	Definition
gCOSMO_RHO0_C	Critical density of the universe [$M_\odot$ kpc^{-3}]
gCOSMO_OMEGA0_M	Present-day pressure-less matter density
gCOSMO_OMEGA0_LAMBDA	Present-day dark energy density
gDM_GAMMARAY_FLAG_SPECTRUM	γ-ray spectrum flag [gENUM_GAMMASPECT]
gDM_MMIN_SUBS	Min. mass of a DM (sub-)clump [$M_\odot$]
gDM_MMAXFACTOR_SUBS	Defines max. mass of clump in host halo as $M_{\rm max}$ = Factor $\times$ $M_{\rm host}$
gDM_RHOSAT	Saturation density [$M_\odot$ kpc^{-3}]
gLIST_HALOES	data/list_generic.txt
gTYPE_CLUMPS_FLAG_CVIRMVIR†	Clump concentration flag in the parent TYPE halo[gENUM_CVIRMVIR]
gTYPE_CLUMPS_FLAG_PROFILE	Clump inner profile flag [gENUM_PROFILE]
gTYPE_CLUMPS_SHAPE_PARAMS[0-2]	Shape parameters for sub-clumps inner profile
gTYPE_DPDM_SLOPE	Slope subclump mass function
gTYPE_DPDV_FLAG_PROFILE	Spatial distribution subclumps [gENUM_PROFILE]
gTYPE_DPDV_RSCALE	Scale radius for the subclump distribution in the parent halo [kpc]
gTYPE_DPDV_SHAPE_PARAMS[0-2]	Shape parameters for the clump spatial distribution
gTYPE_SUBS_MASSFRACTION	Mass fraction of the parent halo in sub-clumps
gGAL_CLUMPS_FLAG_CVIRMVIR	Concentration flag [gENUM_CVIRMVIR]
gGAL_CLUMPS_FLAG_PROFILE	Clump inner profile flag [gENUM_PROFILE]
gGAL_CLUMPS_SHAPE_PARAMS[0-2]	Shape parameter for the Galactic clumps inner profile
gGAL_DPDM_SLOPE	Slope the clump mass function
gGAL_DPDV_FLAG_PROFILE	Clump number distribution flag
gGAL_DPDV_RS	Scale radius for clumps [kpc]
gGAL_DPDV_SHAPE_PARAMS[0-2]	Three shape parameters for the Galactic clump spatial distribution
gGAL_SUBS_M1	Reference mass for gGAL_SUBS_N_INM1M2 [$M_\odot$]
gGAL_SUBS_M2	Reference mass for gGAL_SUBS_N_INM1M2 [$M_\odot$]
gGAL_SUBS_N_INM1M2	# of clumps in [M_1, M_2]
gGAL_RHOSOL	Local DM density [GeV cm^{-3}]
gGAL_RSOL	Distance Sun – Galactic centre [kpc]
gGAL_RVIR	Virial radius of the Galaxy [kpc]
gGAL_TOT_FLAG_PROFILE	Total DM profile of the Milky Way [gENUM_PROFILE]
gGAL_TOT_RSCALE	Scale radius for DM halo of the Milky Way [kpc]
gGAL_TOT_SHAPE_PARAMS[0-2]	Shape parameter for the Galactic total density profile
gSIMU_ALPHAINT_DEG	Integration angle [deg]
gSIMU_EPS	Default precision for numerical integrations
gSIMU_IS_ANNIHIL_OR_DECAY	For annihilating or decaying DM
gSIMU_SEED	Seed of random number generator

† TYPE corresponds to the type of halo under scrutiny (not the Galactic halo): DSPH, GALAXY or CLUSTER are the values allowed by gENUM_TYPEHALOES in this version.

1. General Considerations

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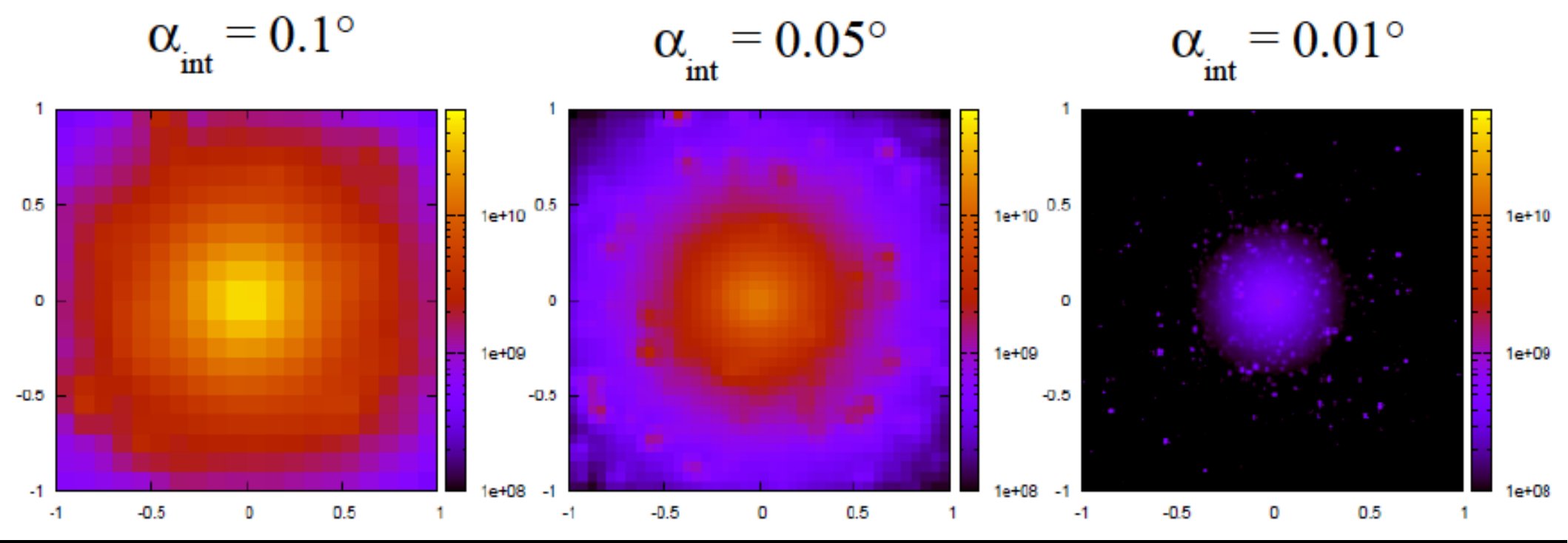
DSph galaxy map

J for a Dsph: 2° x 2°
[core profile + NFW/B01 subclumps]
[d=100 kpc, no galactic background]



Plenty of examples:

http://lpsc.in2p3.fr/clumpy/clumpy_8cc.html#clumpy_examples