CLUMPY: A public code for γ-ray and ν signals from dark matter structures.

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for the CLUMPY developers:
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https://lpsc.in2p3.fr/clumpy/

Bonnivard et al. (CPC, 2016), arXiv:1506.07628
Charbonnier et al. (CPC, 2012), arXiv:1201.4728
Indirect DM detection in γ-rays and ν

Dense & massive astrophysical DM budget → Annihilation or decay of the DM → Detectors for astrophysical γ-rays and neutrinos

Annihilation or decay of the DM

Dense & massive astrophysical DM budget

Detectors for astrophysical γ-rays and neutrinos
Indirect DM detection in $\gamma$-rays and neutrinos

$\gamma$-ray/\nu flux in case of DM annihilation:

\[
\frac{d\Phi_{\gamma}^{\text{ann.}}}{dE_{\gamma}} = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m_{\chi}^2} \times \frac{dN_{\gamma}}{dE_{\gamma}} \times \int_{\Delta\Omega} \int_{l.o.s.} \rho_{\text{DM}}^2 \, dl \, d\Omega
\]

Flux $\propto$ Particle physics $\times J$ : Astrophysical factor $\propto \frac{1}{d^2} \frac{M^2}{V}$

Detection or non-detection:
$J$-factor and uncertainty must be well-known to put constraints on DM candidate

Annihilation: Signal depends crucially on DM target and distribution
(smooth + substructures)

(CLUMPY can also do all calculations for DM decay, but skipped for this talk)
Indirect DM detection in γ-rays and neutrinos

Where to look?

<table>
<thead>
<tr>
<th>Massive &amp; dense ( (M^2/V) )</th>
<th>vs. close ( (1/d^2) )</th>
<th>vs. little astrophysical background</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ single galaxy clusters ( (d &gt; \text{Mpc}) )</td>
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</tr>
<tr>
<td>+ ensemble average of extra-galactic DM ( (d &gt; \text{Gpc}) )</td>
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</table>

**CLUMPY calculates \( J \)-factors/fluxes for all the various targets**

Aquarius simulation – Springel et al. (Nature, 2008)

next release
What is CLUMPY?

- **Open-source**, written in C/C++
- Depends on:
  - CERN’s ROOT
  - Heasarc’s cfitsio
  - HEALPix (next release shipped with frozen HEALPix version)
  - gsl
  - GreAT (lpsc.in2p3.fr/great, optional)
- Runs on **Linux** and **MacOS X**

Open source code to provide the community with reproducible and comparable $J$-factor values
**CLUMPY features (I):** \( \rho_{\text{sm}} + \rho_{\text{subs}} \rightarrow J\text{-factor/flux} \)

\( J\text{-factors/fluxes of individual objects (e.g. dSph’s) from pre-defined DM profiles} \)

- Propagate **error bars from DM profiles to** \( J\text{-factors and limits on DM} \)

- Take into account **substructures:**
  
  - resolved (statistical) + unresolved: **boost**
  
  - vary distribution within host halo (antibiased, own profile,...)

  - Clumps within clumps: multiple levels of self-similar sub-subclustering (converges for ~2 levels)

- allow **triaxial distortion** of halo profile (semiaxis ratio \( a, b, c \))

Comparison of classical dSph, brightest galaxy clusters, and galactic DM foreground

LMC \( dJ/d\Omega \) profile with resolved substructure model (analysis done by M. Castaño, São Paulo)

N-body simulations/kinematic analyses find triaxial halo shapes

Despali et al. (2013)
CLUMPY features (I): \( \rho_{\text{sm}} + \rho_{\text{subs}} \rightarrow J\text{-factor/flux} \)

- Directly compute differential/integral fluxes (1D and 2D), relying on PPPC4DMID (Cirelli et al., 2010)
- ROOT pop-up graphics (1D and 2D)
- Choose output format: ROOT, HEALPix FITS (2D), ASCII
- FITS images interfaceable with gammalib/ctools
- Correct cosmology (line-of-sight and angular diameter distance) + EBL flux absorption for extragalactic objects

\( J \)-factors/fluxes of individual objects (e.g. dSph’s) from **pre-defined DM profiles**

HEALPix pixelization (FITS format)

ROOT plots and output format

Projected FITS image
CLUMPY features (II): Full-sky MW analysis with subhalos

Skymaps of full or partial $J$-factor sky from DM in the Milky Way halo

- Fast realistic synthetic skymaps at any instrumental resolution
  - check that we recover N-body simulation end-products from a handful of parameters
  - extend N-body simulation results by varying key parameters to study impact on halo/substructure brightness
- Resolved substructure
  - Smartly pre-select brightest subhalos for speed (e.g., reduce $10^{15}$ total subhalos in the MW to $\sim10^4$ at a precision of 2% and $\theta_{\text{int}}=0.2^\circ$).
  - allows to do statistical assessment of MW substructure properties (average mass, distance, luminosity, ...)
  - Application in the context of CTA and sensitivity to dark halo searches in Hütten et al., JCAP (2016)

- See my talk in DM session Friday, 2:45 p.m.
CLUMPY features (III): Jeans analysis module

From stellar kinematics to DM profile

- Light profile & velocity dispersion
  \[ I(R) \]
  \[ \sigma^2_p(R) \]

  de-projection

  projection

  stellar density & radial velocity dispersion

- Spherical Jeans equation: solve for \( \bar{v}_r^2 \)
  \[
  \frac{1}{\nu} \frac{d \left( \nu \bar{v}_r^2 \right)}{dr} + \frac{2 \beta_{\text{ani}} \bar{v}_r^2}{r} = -\frac{GM(r)}{r^2}
  \]
  \[ M(r) = 4\pi \int_0^r \rho(r') r'^2 dr' \]
  \[ \beta_{\text{ani}} = 1 - \bar{v}_\theta^2/\bar{v}_r^2 : \text{anisotropy} \]

- Dark matter profile
  \[ \rho(r) = \frac{\rho_s}{\left( \frac{r}{r_s} \right)^\gamma \left[ 1 + \left( \frac{r}{r_s} \right)^\alpha \right]^{\beta - \gamma}} \]

- \( \chi^2 \) or MCMC analysis to extract DM parameters
  \( \rho_s, r_s, \alpha, \beta, \gamma, \) and \( \beta_{\text{ani}} \)
CLUMPY features (III): Jeans analysis module

Dsph galaxy analysis: ranking and/or credible intervals

Many new MW satellite galaxies just discovered (DES) & expected (e.g., LSST): CLUMPY can be used as soon as spectroscopic data is available

Towards the next (3rd) release:

- **Extragalactic module IV**: Compute $\gamma$-ray and $\nu$ fluxes from various extragalactic sources (total isotropic flux + variation)
- Improved output tailored to use CLUMPY with CTA tools (gammalib/ctools)
- Improved user input options (parameter file or command line options)
- Code compilation optimization for easier installation and platform-compatibility.
- Moved to git

- To be released within the next ~6 months (Hütten et al., in prep.)
Summary

CLUMPY: multi-purpose code for indirect DM detection modeling and analysis

• Code distribution and usage:
  ‣ Open-source: reproducible and comparable $J$-factor calculations
  ‣ User-friendly, fully documented using Doxygen, lots of examples & tests to run
  ‣ All runs from single parameter file or command line (profiles, concentration, spectra...)

• Fast computation of:
  ‣ Annihilation or decay astrophysical factors using any DM profile
  ‣ Consistent boost from substructures
  ‣ Integrated/differential fluxes in γ-rays and neutrinos, mixing user-defined branching ratios

• Four main modules / physics cases:
  I. DM emission from list of objects (dSph galaxies, galaxy clusters)
  II. Full-sky map mode for Galactic DM emission with substructure + additional objects from list
  III. Jeans module: full analysis from kinematic data to $J$-factors for dSph
  IV. Full-sky map mode for extragalactic DM emission (coming with the 3rd release)

Growing use in the community for state-of-the-art DM studies for many targets (dSphs, cluster, dark clumps...) and by several collaborations (ANTARES, HAWC, CTA)

Download [https://lpsc.in2p3.fr/clumpy/](https://lpsc.in2p3.fr/clumpy/) + stay tuned for 3rd release!
Thanks for your attention
$J_{\text{tot}}$ integration, substructures, and boost factor

- Simple or “smooth” DM density profile:
  No analytic $J$-factor expression for usual NFW, Einasto,...
  DM density profiles

  $$\frac{dJ_{\text{sm}}(\theta)}{d\Omega} = \int_{l_{\text{min}}}^{l_{\text{max}}} \rho_{\text{sm}}^2 \, dl$$

  - numeric line-of-sight integration needed

- DM substructure:
  For DM annihilation, we have a boost from unresolved substructures in the halo, $J = J_{\text{sm}} + \langle J_{\text{sub}} \rangle = \text{boost} \times J_{\text{sm}}$

  $$\left\langle \frac{dJ_{\text{sub}}(\theta)}{d\Omega} \right\rangle = N_{\text{tot}} \int_{l_{\text{min}}}^{l_{\text{max}}} \frac{dP_{\text{V}}}{dV} (l) \, dl \int_{M_{\text{min}}}^{M_{\text{max}}} L(M) \frac{dP_{\text{M}}}{dM} \, dM$$

  - depending on $dP/dV$, $J_{\text{sub}}(\theta)$ not proportional to $J_{\text{sm}}(\theta)$!

**CLUMPY** does the fast numeric multi.-dim. integration of all the $J$-factor ingredients

- dSph: $\text{boost}(\theta) \sim 1 - 2$
- Galaxy cluster: $\text{boost}(\theta) \sim 10 - 100$
$J_{\text{tot}}$ integration, substructures, and boost factor

\[ J = \int_{0}^{\Delta \Omega} \int_{l_{\text{min}}}^{l_{\text{max}}} \frac{1}{l^2} \left( \rho_{\text{sm}} + \sum_{i} \rho_{\text{cl}}^{i} \right)^2 l^2 dld\Omega \]

up to 20% of $J_{\text{tot}}$ in some config.

\[ J_{\text{sm}} = \int_{0}^{\Delta \Omega} \int_{l_{\text{min}}}^{l_{\text{max}}} \rho_{\text{sm}}^2 dld\Omega \]

\[ J_{\text{cross-prod}} = 2 \int_{0}^{\Delta \Omega} \int_{l_{\text{min}}}^{l_{\text{max}}} \rho_{\text{sm}} \sum_{i} \rho_{\text{cl}}^{i} dld\Omega \]

\[ J_{\text{subs}} = \int_{0}^{\Delta \Omega} \int_{l_{\text{min}}}^{l_{\text{max}}} \left( \sum_{i} \rho_{\text{cl}}^{i} \right)^2 dld\Omega \]

exact realisation (mass and position) of DM distribution unknown

Average description using mass and spatial distribution from simulations

\[ \langle J_{\text{cross-prod}} \rangle = 2 \int_{0}^{\Delta \Omega} \int_{l_{\text{min}}}^{l_{\text{max}}} \rho_{\text{sm}} \langle \rho_{\text{subs}} \rangle dld\Omega \]

\[ \langle J_{\text{subs}} \rangle = N_{\text{tot}} \int_{0}^{\Delta \Omega} \int_{l_{\text{min}}}^{l_{\text{max}}} \frac{dP_{V}}{dV} dld\Omega \int_{M_{\text{min}}}^{M_{\text{max}}} \mathcal{L}(M) \frac{P_{M}}{dM} dM \]

\[ \mathcal{L}(M) \equiv \int_{V_{\text{cl}}} (\rho_{\text{cl}})^2 dV \]
Multi-level boost

- Signal converges quickly
All parameters controlled from parameter file

<table>
<thead>
<tr>
<th>Name</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cosmological parameters</strong> (updated from Planck results)</td>
<td></td>
</tr>
<tr>
<td>gCGSMO_HUBBLE</td>
<td>Hubble expansion rate $h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1}) \text{ [-]}$</td>
</tr>
<tr>
<td>gCGSMO_RHOO_C</td>
<td>Critical density of the universe $[M_\odot \text{ kpc}^{-3}]$</td>
</tr>
<tr>
<td>gCGSMO_OMEGA0_M</td>
<td>Present-day pressure-less matter density</td>
</tr>
<tr>
<td>gCGSMO_OMEGA0_LAMBDA</td>
<td>Present-day dark energy density</td>
</tr>
<tr>
<td><strong>Dark matter parameters</strong></td>
<td></td>
</tr>
<tr>
<td>gDM_FLAG_CVIR_DIST</td>
<td>Distribution around $\bar{c}(M)$ from which concentrations are drawn: ${k\text{LOGNORM, kDIRAC}}$</td>
</tr>
<tr>
<td>gDM_LOGCVIR_STDDEV</td>
<td>Width of log-normal $c(M)$ distribution (if gDM_FLAG_CVIR_DIST=$k\text{LOGNORM}$)</td>
</tr>
<tr>
<td>gDM_SUBS_NUMBEROFLEVELS</td>
<td>Number of levels for subhaloes</td>
</tr>
<tr>
<td>gDM_MININ_SUBS</td>
<td>Minimal mass of DM haloes $[M_\odot]$</td>
</tr>
<tr>
<td>gDM_MMAXFRAC_SUBS</td>
<td>Defines the maximal mass of clump in host halo: $M_{\text{max}} = gDM_MMAXFRAC_SUBS \times M_{\text{host}}$</td>
</tr>
<tr>
<td>gDM_RHOSAT</td>
<td>Saturation density for DM $[M_\odot \text{ kpc}^{-3}]$</td>
</tr>
<tr>
<td><strong>Generic (sub-)halo structural parameters</strong></td>
<td></td>
</tr>
<tr>
<td>gTYPE_CLUMPS.{FLAG_PROFILE, ...}</td>
<td>Description of subhaloes for host TYPE: $c(M)$, inner profile, shape parameters</td>
</tr>
<tr>
<td>gTYPE_DPM.DSlope</td>
<td>Slope of the clump mass function</td>
</tr>
<tr>
<td>gTYPE_DPDV.{FLAG_PROFILE, RSCALE, ...}</td>
<td>Spatial distribution of substructures in object TYPE</td>
</tr>
<tr>
<td>gTYPE_SUBS_MASSFRACTION</td>
<td>Mass fraction of the host halo in clumps</td>
</tr>
<tr>
<td><strong>Milky-Way DM (sub-)halo structural parameters</strong></td>
<td></td>
</tr>
<tr>
<td>gGAL_CLUMPS.{FLAG_PROFILE, ...}</td>
<td>Description of Milky-way DM subhaloes</td>
</tr>
<tr>
<td>gGAL_DPM.Slope</td>
<td>Slope of clump mass function</td>
</tr>
<tr>
<td>gGAL_DPDV.{FLAG_PROFILE, RSCALE, ...}</td>
<td>Spatial distribution of substructures in object TYPE</td>
</tr>
<tr>
<td>gGAL_SUBS.{M1, M2, N_INM1M2}</td>
<td>Number of Milky-Way subhaloes in $[M_1, M_2]$</td>
</tr>
<tr>
<td>gGAL_RHOSOL, RSOL, RVIR</td>
<td>Local DM density $[\text{GeV cm}^{-3}]$, distance GC–Sun [kpc], virial radius [kpc]</td>
</tr>
<tr>
<td>gGAL_TOT.{FLAG_PROFILE, RSCALE, ...}</td>
<td>Description of the total DM profile</td>
</tr>
<tr>
<td>gGAL_TRIAXIAL_AXES[0-3]</td>
<td>Dimensionless major ($a$), intermediate ($b$), and minor ($c$) axes (see Eq. (18))</td>
</tr>
<tr>
<td>gGAL_TRIAXIAL_ROTANGLES[0-3]</td>
<td>Euler rotation angles for triaxial Milky-Way halo [deg]</td>
</tr>
<tr>
<td>gGAL_TRIAXIAL_IS</td>
<td>Switch-on or off triaxiality calculation (i.e., use or not the 2 parameters above)</td>
</tr>
</tbody>
</table>
All parameters controlled from parameter file

**Particle physics ingredients** (for $\gamma$-ray and $\nu$ flux calculation)

- **gPP_BR (gPP_BR, gPP_BR**): List of comma-separated values of branching ratios for the 28 channels.
- **gPP_DM ANNIHIL.DELTA**: For annihilating DM, factor 2 in calculation if Majorana, 4 if Dirac.
- **gPP_DM ANNIHIL.SIGMAV.CM3PERS**: For annihilating DM, velocity averaged cross-section $\langle \sigma v \rangle_0$ [cm$^3$ s$^{-1}$].
- **gPP_DM DECAY.LIFETIME.S**: For decaying DM, lifetime $\tau_{DM}$ of DM candidate [s].
- **gPP_DM.IS ANNIHIL.OR DECAY**:
  - Switch for annihilating or decaying DM (replace deprecated `gSIMU.IS ANNIHIL.OR DECAY`).
- **gPP_DM.MASS.GEV**:
  - Mass $m_{DM}$ of the DM candidate [GeV].
- **gPP_FLAG.SPECTRUMMODEL**:
  - Model to calculate final state (replace deprecated `gDM GAMMARAY_FLAG.SPECTRUM`).
- **gPP_NUMIXING.THETA(12, 13, 23).DEG**:
  - Neutrino mixing angles [deg].

**Simulation parameters/outputs** (for a given CLUMPY run)

- **gLIST.HALOES**:
  - Objects considered in Jeans’s analysis [default=data/list.generic.txt].
- **gLIST.HALOES JEANS**:
  - Integration angle $\alpha_{int}$ [deg] (if `gSIMU.HEALPIX(NSIDE not -1`, use HEALPix resolution).
- **gSIMU.EPS**:
  - Precision used for any operation requiring one (numerical integration, ...).
- **gSIMU.SEED**:
  - Seed of random number generator to draw clumps (if 0, from computer clock).
- **gSIMU.FLAG.NUFLAVOUR**:
  - Choice of neutrino flavour ($kNUE$, $kNUMU$, $kNUTAU$).
- **gSIMU.FLUX.AT.E.GEV**:
  - Energy (GeV) at which to calculate fluxes.
- **gSIMU.FLUX.E.MIN**:
  - Lower energy bound (GeV) for the integrated flux calculation.
- **gSIMU.FLUX.E.MAX**:
  - Upper energy bound (GeV) for the integrated flux calculation.
- **gSIMU.GAUSSBEAM.GAMMA.FWHM.DEG**:
  - Gaussian beam [deg] for $\gamma$-ray detector for skymaps smoothing (no smoothing if set to -1).
- **gSIMU.GAUSSBEAM.NEUTRINO.FWHM.DEG**:
  - Gaussian beam [deg] for $\nu$ detector for skymaps smoothing (no smoothing if set to -1).
- **gSIMU.HEALPIX.NSIDE**:
  - $N_{side}$ of HEALPix maps (if -1, set to be as close as possible to $\alpha_{int}$).
- **gSIMU.HEALPIX.RING.WEIGHTS.DIR**:
  - Ring weights directory for improved quadrature (optional).
- **gSIMU.IS ASTRO.OR PP.UNIT**:
  - Outputs (plots and files) in astro ($M_\odot$ and kpc) or particle physics (GeV and cm) units.
- **gSIMU.IS WRITE FLUXMAPS**:
  - For 2D skymaps, whether to save or not $\gamma$-ray and $\nu$ fluxes (the $J$ factor is always saved).
- **gSIMU.IS WRITE FLUXMAPS.INTEGROR DIFF**:
  - If `gSIMU.IS_WRITE_FLUXMAPS` is true, whether to save integrated or differential fluxes.
- **gSIMU.IS WRITE GALPOWERSPECTRUM**:
  - Whether to calculate (and save) or not the DM power-spectrum for the Milky-Way.
- **gSIMU.IS WRITE.ROOTFILES**:
  - Whether to save or not .root files even if option `-p` is used (not enabled for skymaps and 'stat').
- **gSIMU.OUTPUT.DIR**:
  - Output directory to select other than local run (directory is output if set to -1).