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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MAGIC Dark Matter Workshop,
IEEC Barcelona, Jan 16 2019

http://lpsc.in2p3.fr/clumpy/

Hütten et al. (CPC, 2018), arXiv:**1806.08639**
Bonnivard et al. (CPC, 2016), arXiv:**1506.07628**
Charbonnier et al. (CPC, 2012), arXiv:**1201.4728**

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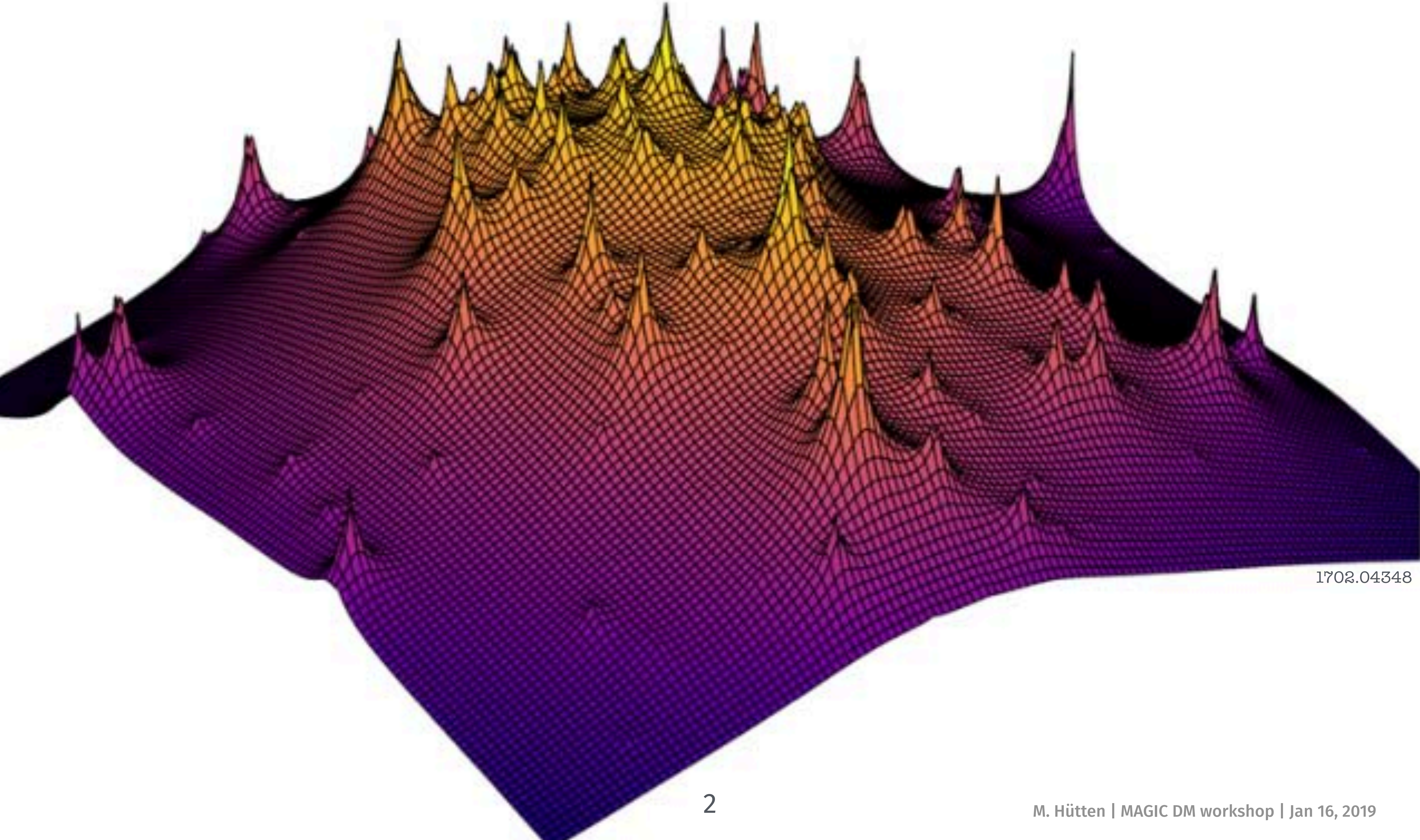
(Werner-Heisenberg-Institut)

Enigmass

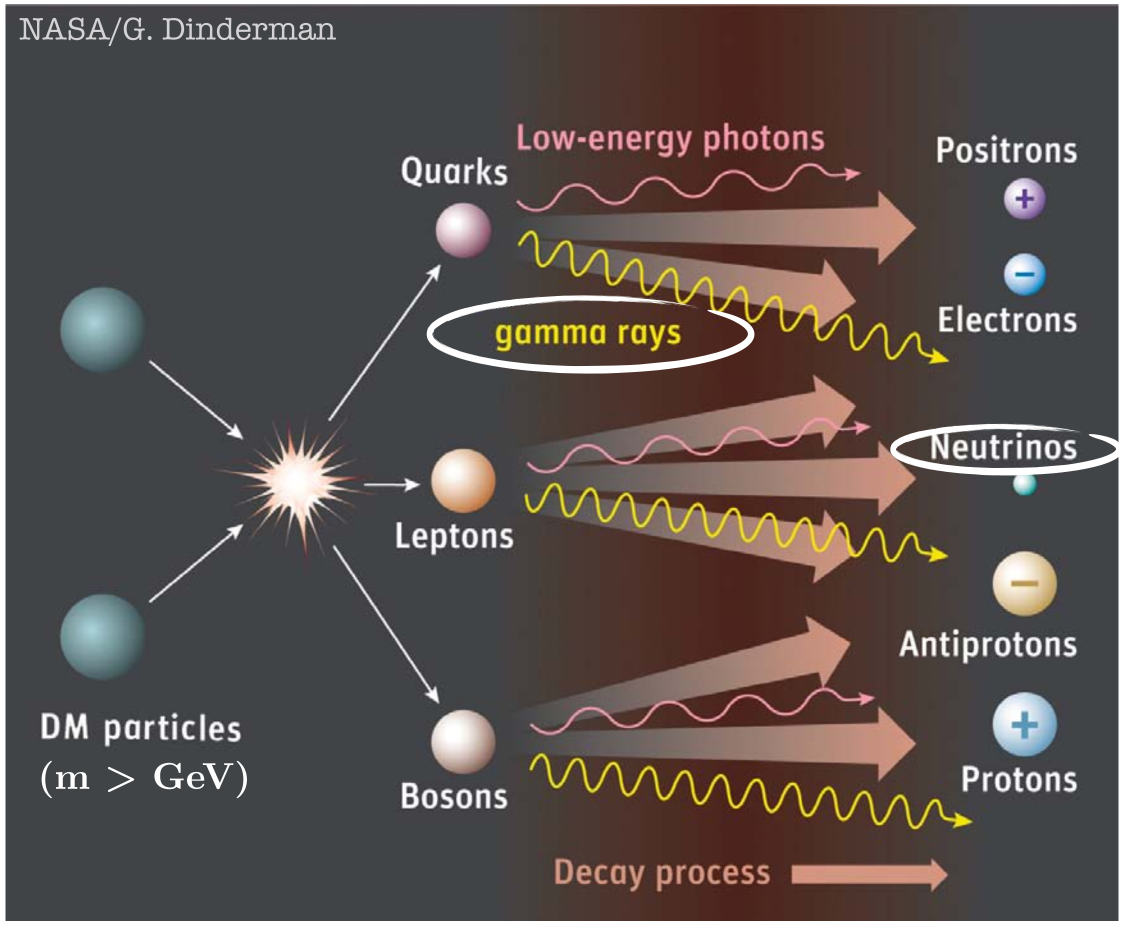
1. Introduction - physics problem

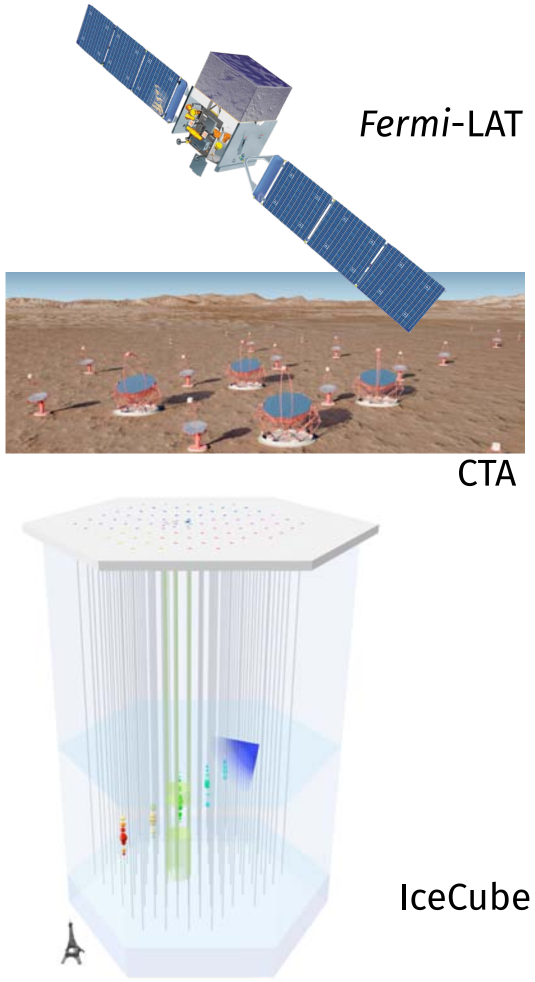


1702.04348

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



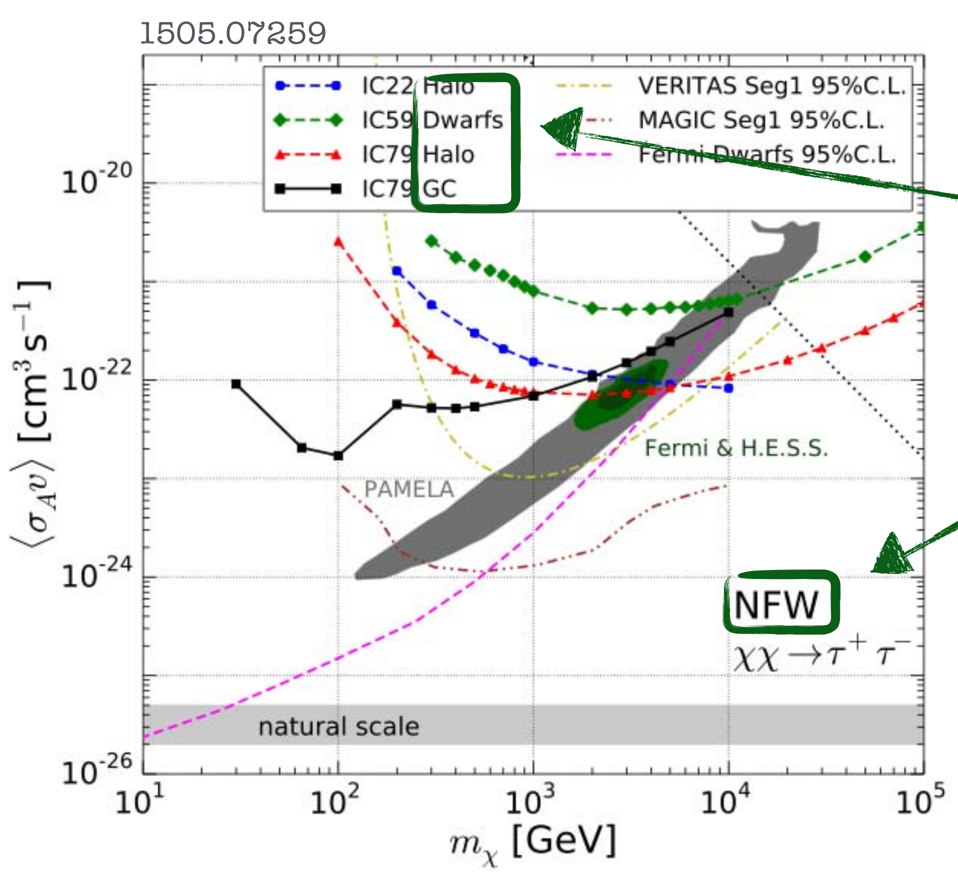


Indirect DM detection in neutral particles

Prompt γ-ray/ν flux for single source & DM **annihilation:** (CLUMPY can also do all calculations for DM **decay**)

$$\frac{\mathrm{d}\Phi^{\mathrm{ann}}}{\mathrm{d}E_{\mathrm{obs}}} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{\delta\, m_\chi^2} \times \frac{\mathrm{d}N_\nu}{\mathrm{d}E_{\mathrm{source}}}\left([1+z]\,E_{\mathrm{obs}}\right) \times \int_{\Delta\Omega}\int_{l.o.s.} \rho_{\mathrm{DM}}^2\, \mathrm{d}l\, \mathrm{d}\Omega \times (1+z)^3$$

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



Detection or non-detection:

J-factor and uncertainty must be well-known for conclusions on particle physics

Annihilation: Signal depends sensibly on DM distribution in target

E.g., innermost $0.1°$ Galactic DM halo:

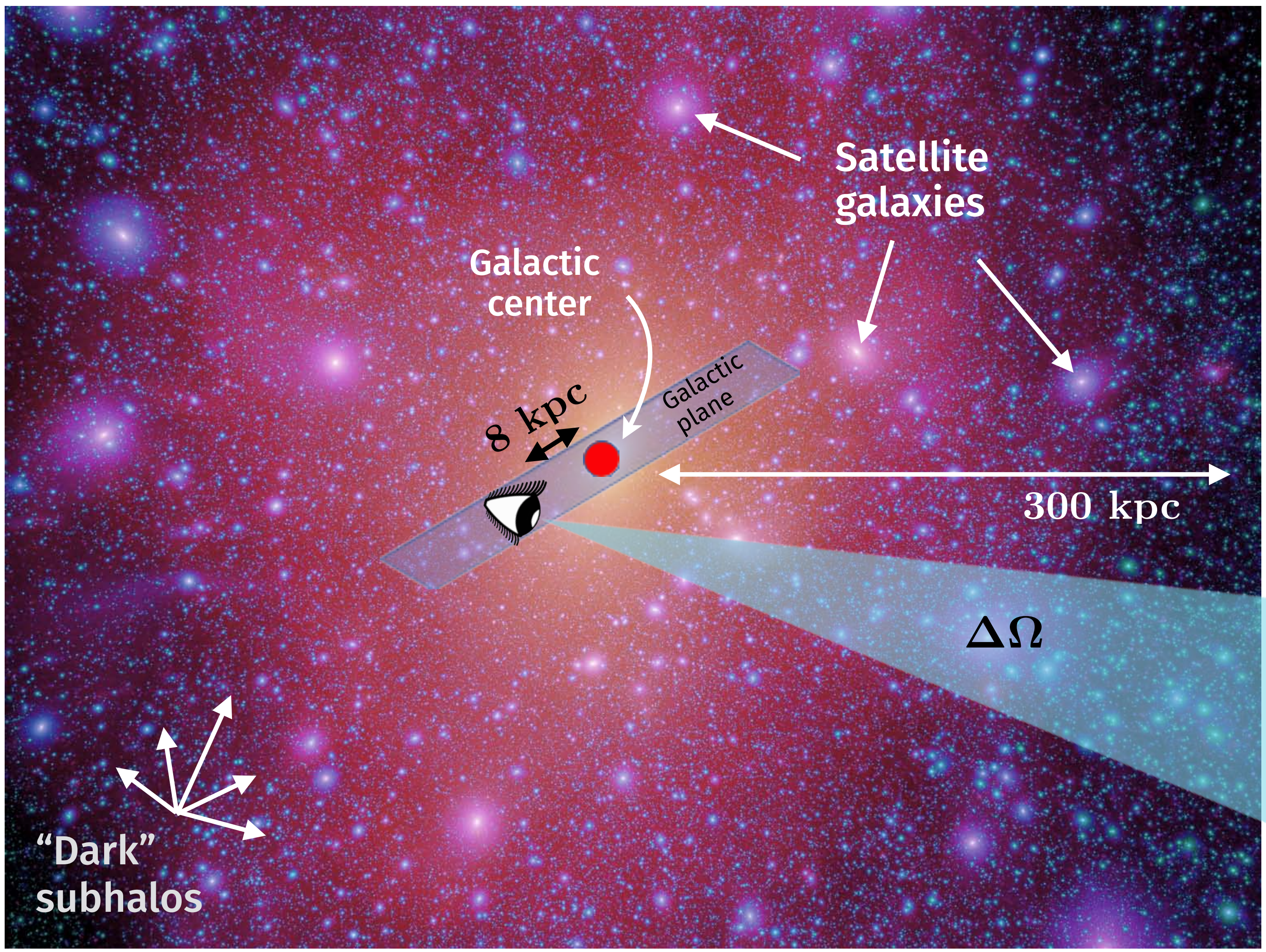
NFW or Einasto vs. ***Burkert*** profile,

annihilation: Factor **2000**, Decay: Factor **10**

J-factor main uncertainty in indirect DM searches

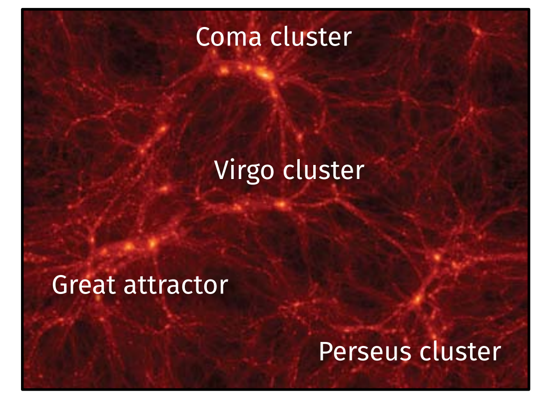
Where to look?

Massive & dense (M^2/V) vs. close ($1/d^2$) vs. little astrophysical background



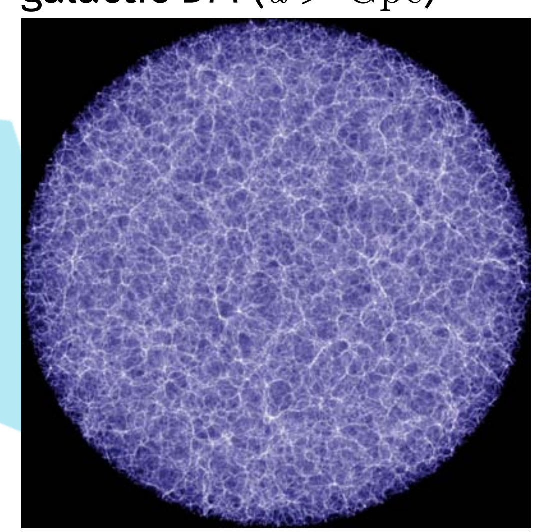
Aquarius simulation – Springel et al. (Nature, 2008)

+ single galaxy clusters ($d > \mathrm{Mpc}$)



Gottlöber et. al. (2010)

+ ensemble average of extra-galactic DM ($d > \mathrm{Gpc}$)



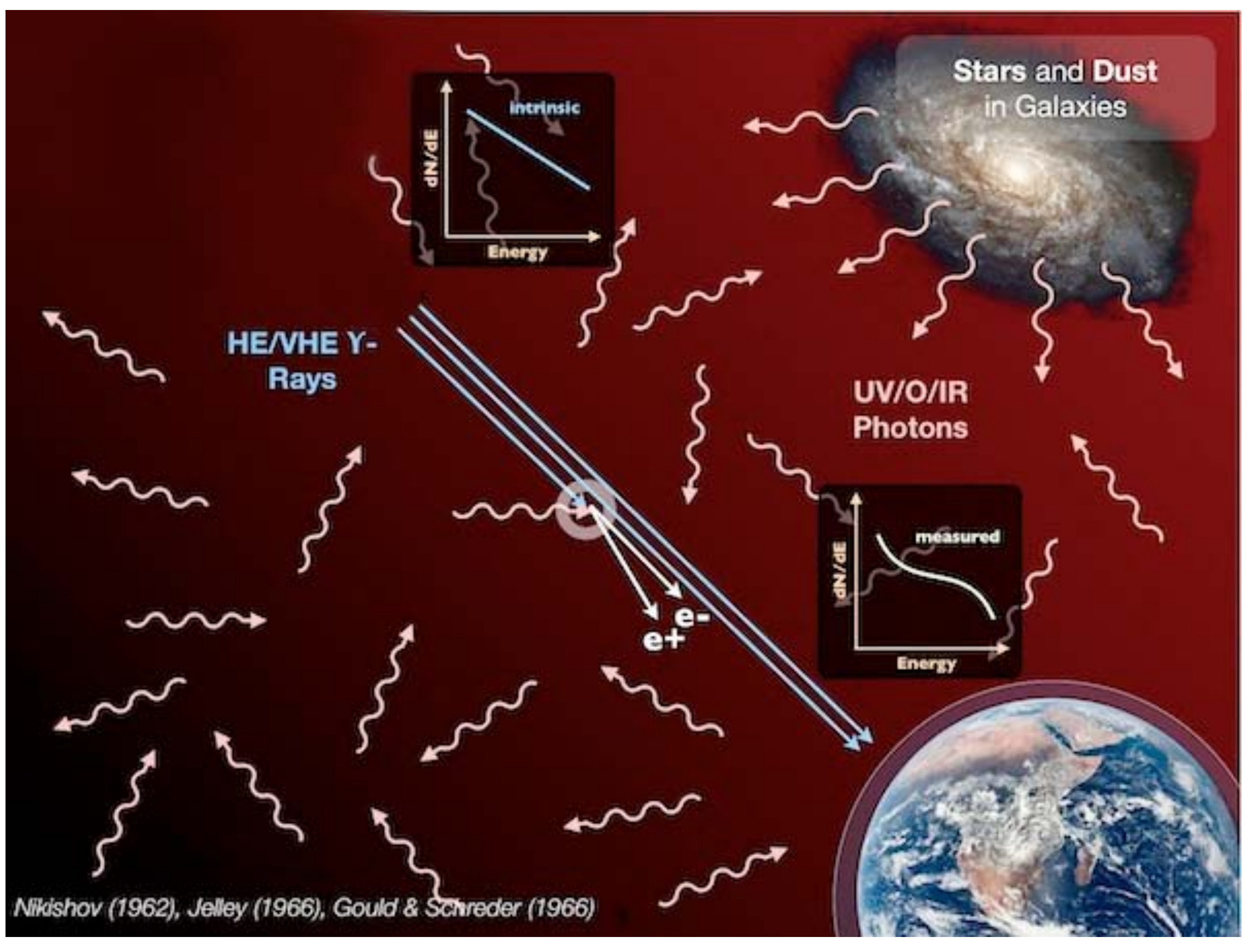
Angulo et al. (2008)

CLUMPY calculates J-factors/fluxes for all the various targets

Indirect DM detection in extragalactic γ-rays

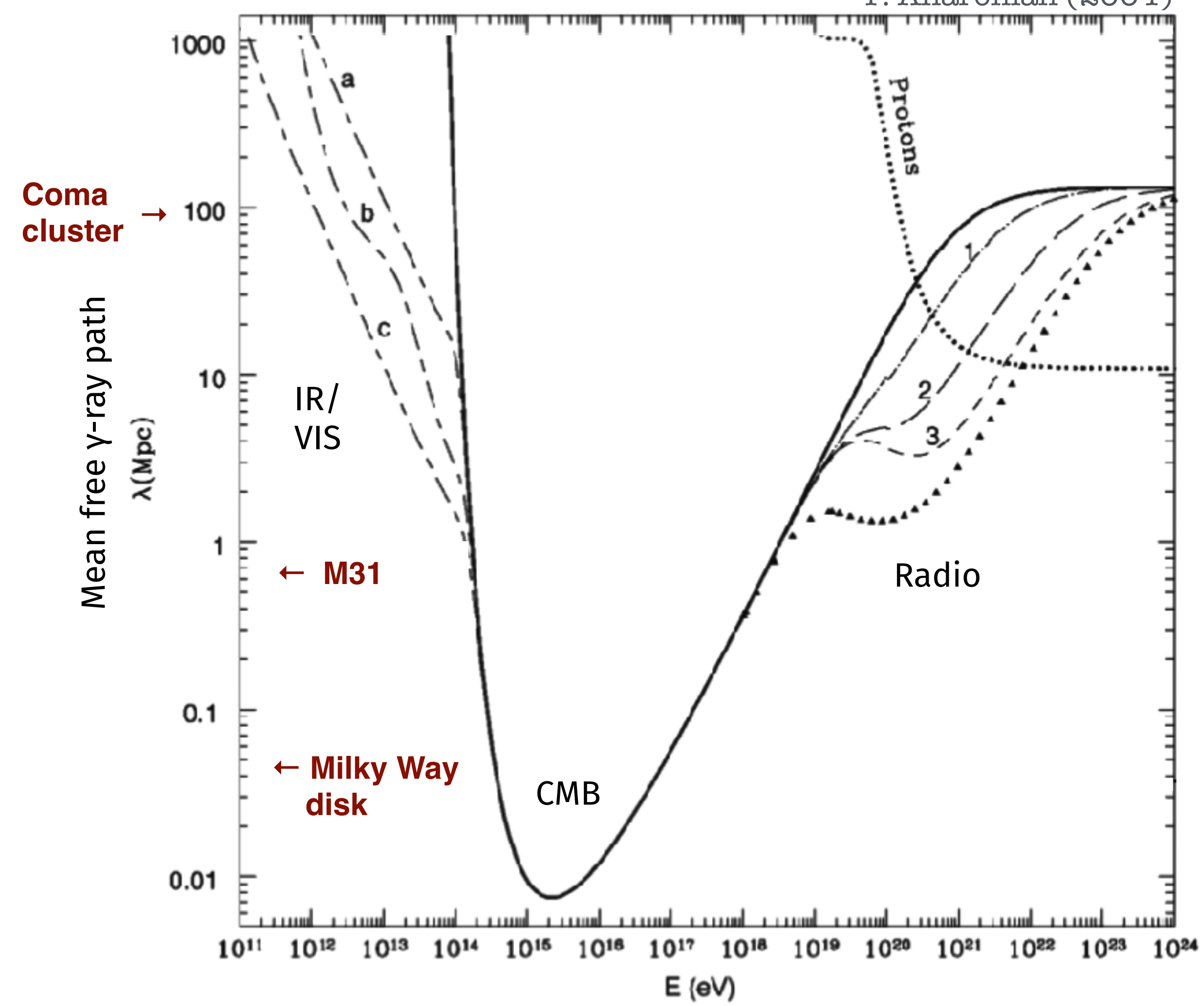
Consider for γ-rays from outside the local Universe

- Redshifting of the γ-rays/ neutrino energy loss
- γ-rays absorption by pair-production with photons of the extragalactic background light (EBL)



LEXI, University of Hamburg

F. Aharonian (2004)



Indirect DM detection in extragalactic γ-rays

➡ More intricate form of flux equation (single extragalactic object):

EBL absorption

$$\frac{d\Phi_\gamma^{\mathrm{ann.}}}{dE_\gamma^{\mathrm{obs}}} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2} \times \frac{dN_\gamma}{dE_\gamma^{\mathrm{source}}}\left(\left[1+z\right]E_\gamma^{\mathrm{obs}}\right) \times e^{-\tau(z,E_\gamma)}$$

$$\times\,(1+z)^3 \int_{\Delta\Omega}\int_{l_c} \rho_{\mathrm{DM}}^2\, dl_c\, d\Omega$$

redshift

annihilation boost in smaller proper volume

description in comoving coordinates

➡ Separation in particle physics/astrophysics term **breaks down** if considering a signal originating from multiple redshift shells

A closer look to the *J*-factor

$$J = \int_0^{\Delta\Omega} \int_{l_{\rm min}}^{l_{\rm max}} \frac{1}{l^2} \left(\rho_{\rm sm} + \sum_i \rho_{\rm cl}^i \right)^2 l^2 dl d\Omega$$

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

$$J_{\rm sm} \equiv \int_0^{\Delta\Omega} \int_{l_{\rm min}}^{l_{\rm max}} \rho_{\rm sm}^2 dl d\Omega$$

$$J_{\rm cross-prod} \equiv 2 \int_0^{\Delta\Omega} \int_{l_{\rm min}}^{l_{\rm max}} \rho_{\rm sm} \sum_i \rho_{\rm cl}^i dl d\Omega$$

$$J_{\rm subs} \equiv \int_0^{\Delta\Omega} \int_{l_{\rm min}}^{l_{\rm max}} \left(\sum_i \rho_{\rm cl}^i \right)^2 dl d\Omega$$

exact realisation (mass and position) of DM distribution unknown

Average description using mass and spatial distribution from simulations

$$\langle J_{\rm cross-prod} \rangle = 2 \int_0^{\Delta\Omega} \int_{l_{\rm min}}^{l_{\rm max}} \rho_{\rm sm} \langle \rho_{\rm subs} \rangle dl d\Omega$$

$$\langle J_{\rm subs} \rangle = N_{\rm tot} \int_0^{\Delta\Omega} \int_{l_{\rm min}}^{l_{\rm max}} \frac{d\mathcal{P}_V}{dV} dl d\Omega \int_{M_{\rm min}}^{M_{\rm max}} \mathcal{L}(M) \frac{\mathcal{P}_M}{dM} dM$$

$$\mathcal{L}(M) \equiv \int_{\rm V_{cl}} (\rho_{\rm cl})^2 \, dV$$

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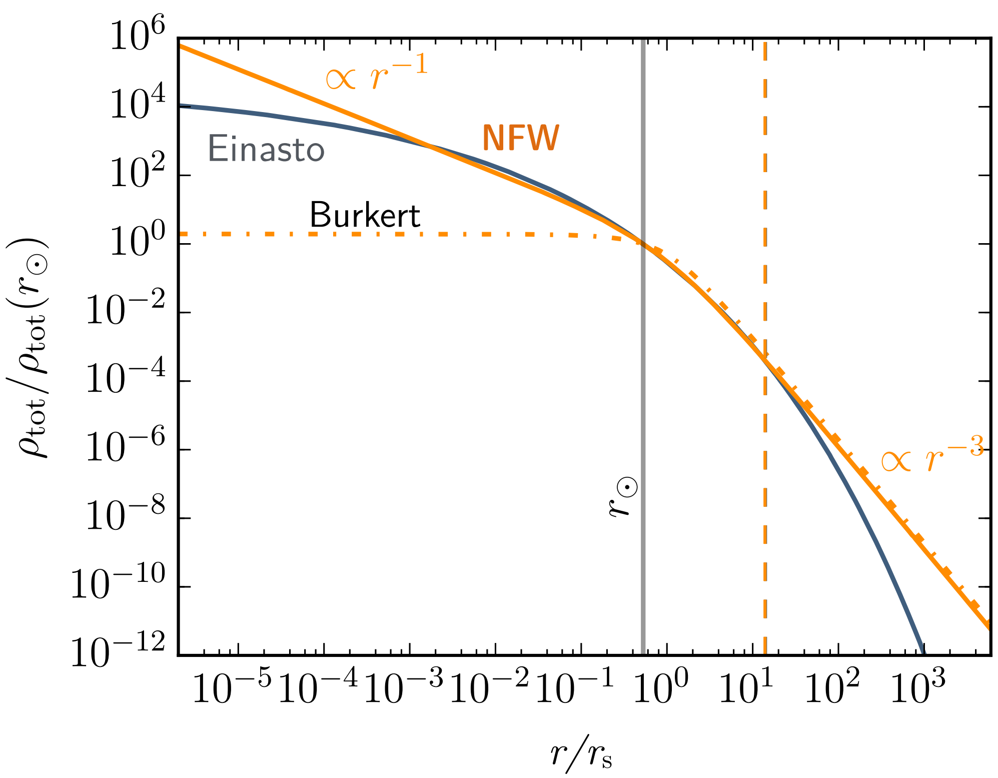
A closer look to the *J*-factor

- No analytic solution for $\frac{\mathrm{d}J_{\rm sm}}{\mathrm{d}\Omega}(\theta) = \int_{l_{\rm min}}^{l_{\rm max}} \rho_{\rm sm}^2 \,\mathrm{d}l$ or $\frac{\mathrm{d}J_{\rm sm}}{\mathrm{d}\Omega}(\theta) = \int_{l_{\rm min}}^{l_{\rm max}} \rho_{\rm sm} \,\mathrm{d}l$ with usual descriptions:



kBURKERT	Burkert (1995): $\rho(r \mid r_0, \rho_0) = \frac{\rho_0}{\left(1+\frac{r}{r_0}\right)\times\left[1+\left(\frac{r}{r_0}\right)^2\right]}$, with $r_{-2} \approx 1.5213797068 \times r_0$ and $\rho_0 = \rho(r=0)$.
kEINASTO	Navarro et al. (2004), Springel et al. (2008): $\rho(r \mid r_{-2}, \rho_{-2}; \alpha) = \rho_{-2}\, \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_{-2}}\right)^\alpha - 1\right]\right\}$
kEINASTO_N	Merritt et al. (2006), Graham et al. (2006): $\rho(r \mid r_{\rm e}, \rho_{\rm e}; n) = \rho_{\rm e}\, \exp\left\{-d_n \times \left[\left(\frac{r}{r_{\rm e}}\right)^{1/n} - 1\right]\right\}$, with $d_n \approx 3n - \frac{1}{3} + \frac{0.0079}{n}$ (see Merritt et al. (2006)) and $r_{-2} = r_{\rm e} \times \left(\frac{2n}{d_n}\right)^n$
kZHAO	Hernquist (1990) and Zhao (1996): $\rho(r \mid r_{\rm s}, \rho_{\rm s}; \alpha, \beta, \gamma) = \frac{2^{\frac{\beta-\gamma}{\alpha}} \times \rho_{\rm s}}{\left(\frac{r}{r_{\rm s}}\right)^\gamma \times \left[1+\left(\frac{r}{r_{\rm s}}\right)^\alpha\right]^{\frac{\beta-\gamma}{\alpha}}}$, with $r_{-2} = r_{\rm s} \times \left(\frac{\beta-2}{2-\gamma}\right)^{-1/\alpha}$. Note that we use the description where $\rho_{\rm s} = \rho(r_{\rm s})$.

- CLUMPY: *J*-factor integrator (with accounting for many subtleties)

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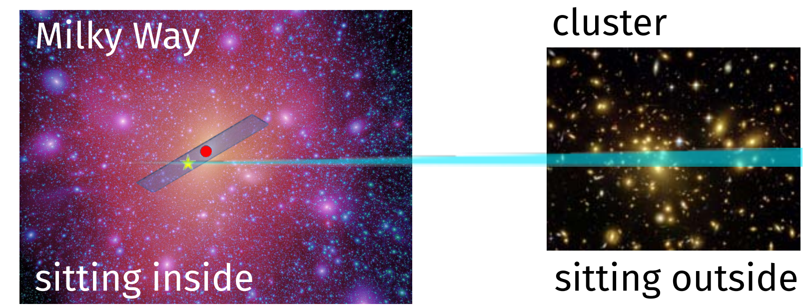
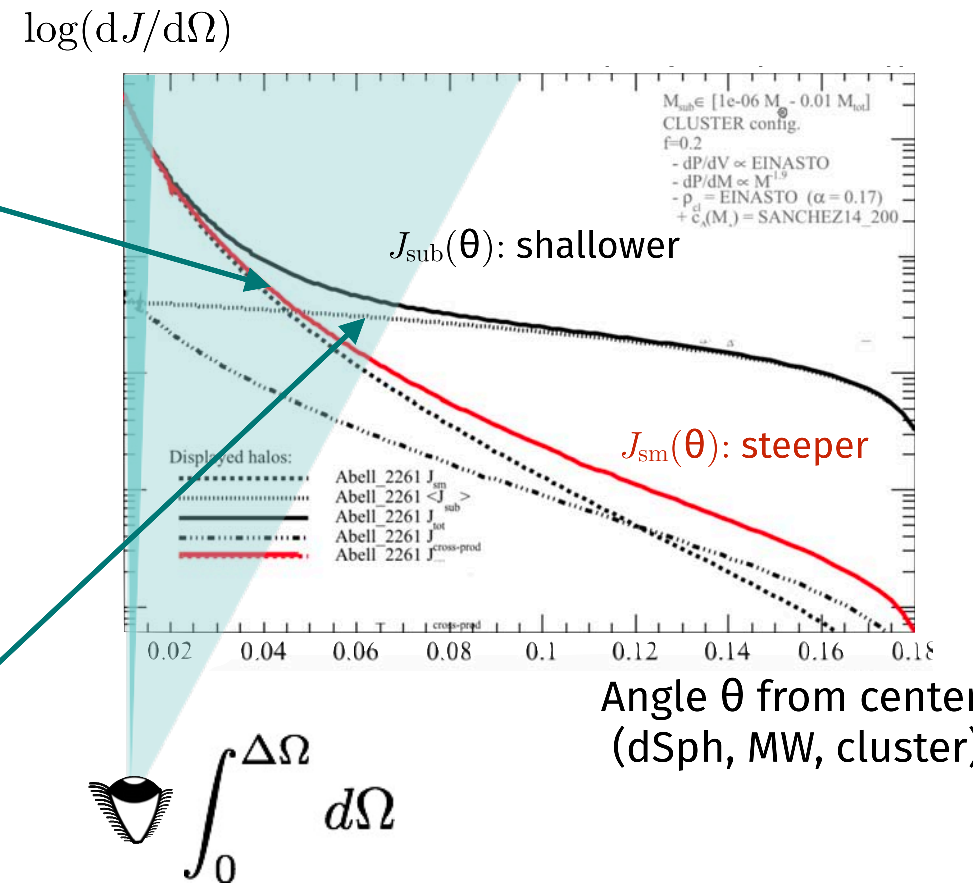
A closer look to the *J*-factor: substructures and boost

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

$$\frac{\mathrm{d}J_{\mathrm{sm}}}{\mathrm{d}\Omega}(\theta) = \int_{l_{\mathrm{min}}}^{l_{\mathrm{max}}} \rho_{\mathrm{sm}}^2 \,\mathrm{d}l$$

- numeric line-of-sight integration needed





- Even more complicated with DM substructure:

$$\left\langle \frac{\mathrm{d}J_{\mathrm{sub}}}{\mathrm{d}\Omega}(\theta) \right\rangle = N_{\mathrm{tot}} \int_{l_{\mathrm{min}}}^{l_{\mathrm{max}}} \frac{\mathrm{d}P_V}{\mathrm{d}V}(l)\,\mathrm{d}l \int_{M_{\mathrm{min}}}^{M_{\mathrm{max}}} \mathcal{L}(M) \frac{\mathrm{d}P_M}{\mathrm{d}M}\,\mathrm{d}M$$

  - depending on $\mathrm{d}P/\mathrm{d}V$, $J_{\mathrm{sub}}(\theta)$ not proportional to $J_{\mathrm{sm}}(\theta)$!

- Additionally, $J_{\text{cross-prod}}$

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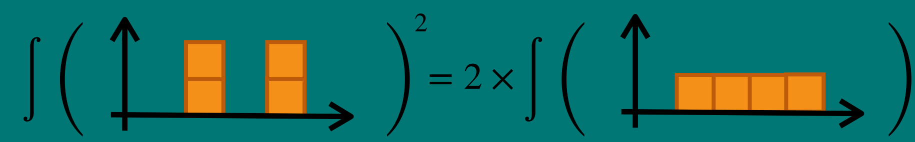
Annihilation boost in substructures



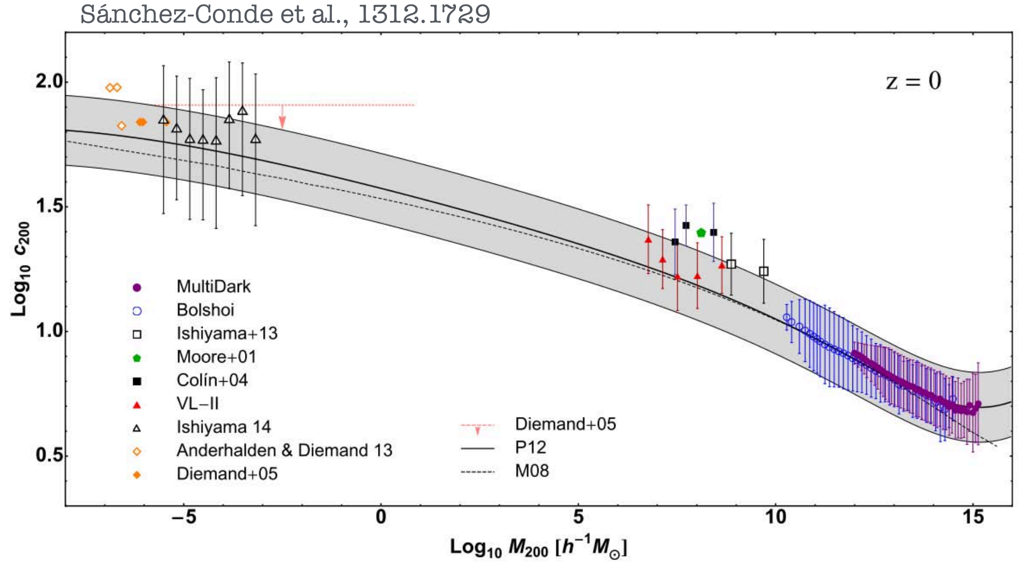
Substructure boost $= \dfrac{J_{\rm smooth} + \langle J_{\rm cross-prod}\rangle + \langle J_{\rm sub}\rangle}{J_{\rm no\ subs}} - 1$ (*)

dSph: boost $\sim 1-2$

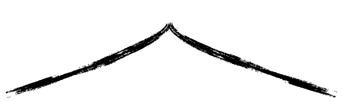
Galaxy cluster: boost $\sim 10-100$

$$\left\langle \frac{\mathrm{d}J_{\rm sub}}{\mathrm{d}\Omega}(\theta)\right\rangle = N_{\rm tot}\int_{l_{\rm min}}^{l_{\rm max}} \frac{\mathrm{d}P_V}{\mathrm{d}V}(l)\,\mathrm{d}l \int_{M_{\rm min}}^{M_{\rm max}} \mathcal{L}(M)\frac{\mathrm{d}P_M}{\mathrm{d}M}\,\mathrm{d}M$$

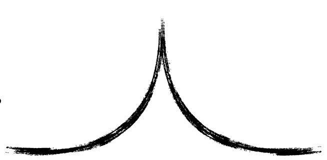
Sánchez-Conde et al., 1312.1729



Substructure luminosity sensible to substructure concentration



vs.



Concentration: measure of the "spikyness" of a halo:
Defined as

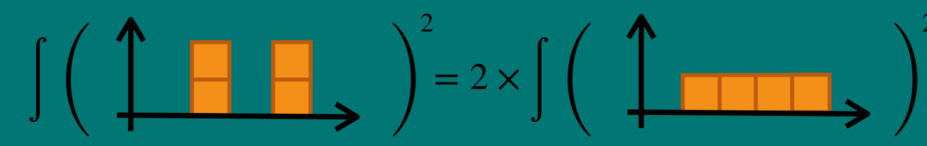
$$c = r_{-2}/R_\Delta$$

Lots of descriptions in CLUMPY

Keyword	Description
kB01_VIR	Bullock et al. (2001): extrapolation down to any mass range. $C_i = \{-4.34,\ 0.0384,\ -3.91\times10^{-4},\ -2.2\times10^{-6},\ -5.5\times10^{-7}\}$
kB01_VIR_RAD	Kuhlen et al (2008): adaption of Bullock et al. (2001) with radial dependence.
kCORREA15_PLANCK_200	Correa et al. (2015): Only for extragalactic haloes and Planck cosmology.
kENS01_VIR	Eke et al. (2001): extrapolation down any mass range. $C_i = \{3.14,\ -0.018,\ -4.1\times10^{-4}\}$
kNETO07_200	Neto et al. (2007): valid for $M > 10^8 M_\odot$. $c_{200} = 4.67\times\left(\frac{M_{200}}{10^{14}M_\odot}\right)^{-0.11}\times\ (1+z)^{-1}$ [their Eq. 5].
kDUFFY08F_VIR	Duffy et al. (2008), $\Delta = \Delta_{\rm vir}(z)$: valid for $M > 10^8 M_\odot$. $c_{\rm vir} = A\left(\frac{M_{\rm vir}}{2{\times}10^{12}M_\odot}\right)^B(1+z)^C$ [see their Table 1 for A, B, C].
kDUFFY08F_200	Duffy et al. (2008), $\Delta = 200$: valid for $M > 10^8 M_\odot$.
kDUFFY08F_MEAN	Duffy et al. (2008), $\Delta = 200\times\Omega_{\rm mean}(z)$: valid for $M > 10^8 M_\odot$.
kETTORI10_200	Ettori et al. (2010): valid for $M > 10^8 M_\odot$ $c_{200} = 10^{0.62}\times\left(\frac{M_{200}}{10^{15}M_\odot}\right)^{-0.1}\times\ (1+z)^{-1}$ [see their Eq. 5].
kGIOCOLI12_VIR	Giocoli et al. (2012): extrapolation down to any mass range.
kLUDLOW16_200	Ludlow et al. (2016): Only for extragalactic haloes and Planck cosmology.
kMOLINE17_200	Moliné et al. (2017), Eq. (6): improvement on Sánchez-Conde & Prada (2014) for Galactic subhalos accounting for spatial dependence of subhalos in field halos.

(*) Miguel's talk yesterday

Annihilation boost in substructures



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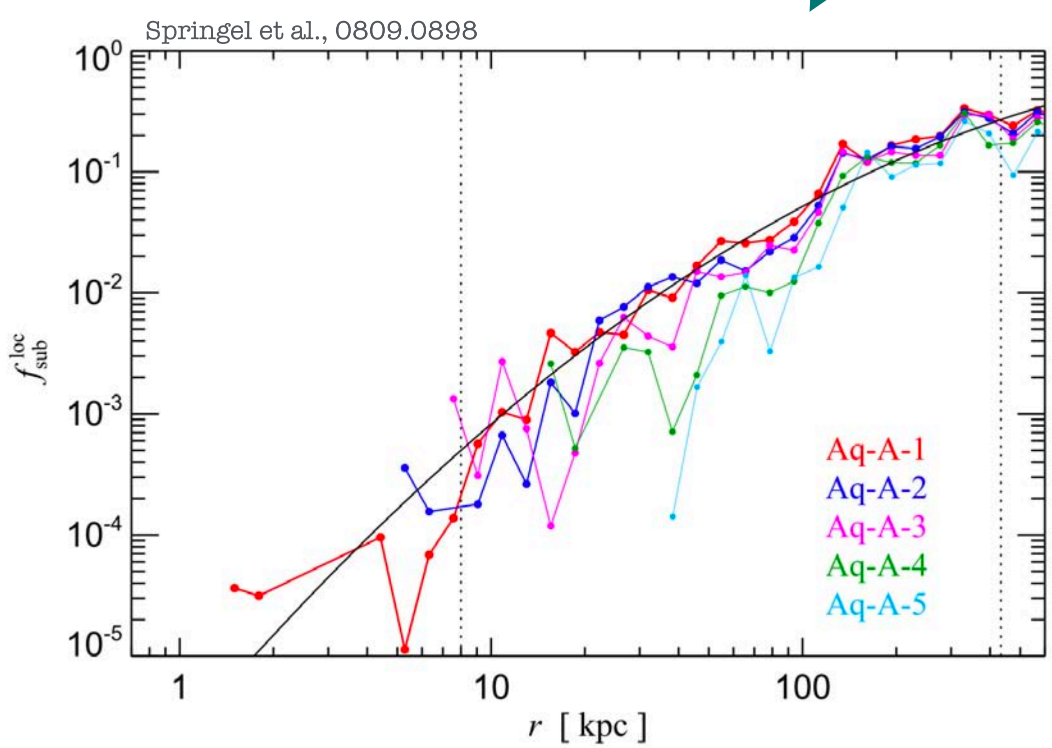
dSph: boost $\sim 1-2$

Galaxy cluster: boost $\sim \mathbf{10-100}$

Fraction of halo mass bound in substructure

$$\left\langle \frac{\mathrm{d}J_{\rm sub}}{\mathrm{d}\Omega}(\theta)\right\rangle = N_{\rm tot}\int_{l_{\rm min}}^{l_{\rm max}} \frac{\mathrm{d}P_V}{\mathrm{d}V}(l)\,\mathrm{d}l \int_{M_{\rm min}}^{M_{\rm max}} \mathcal{L}(M)\frac{\mathrm{d}P_M}{\mathrm{d}M}\,\mathrm{d}M$$

Spatial distribution inside the host halo



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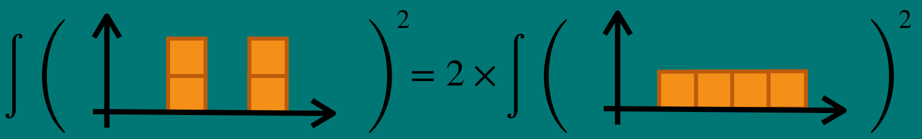
Annihilation boost in substructures



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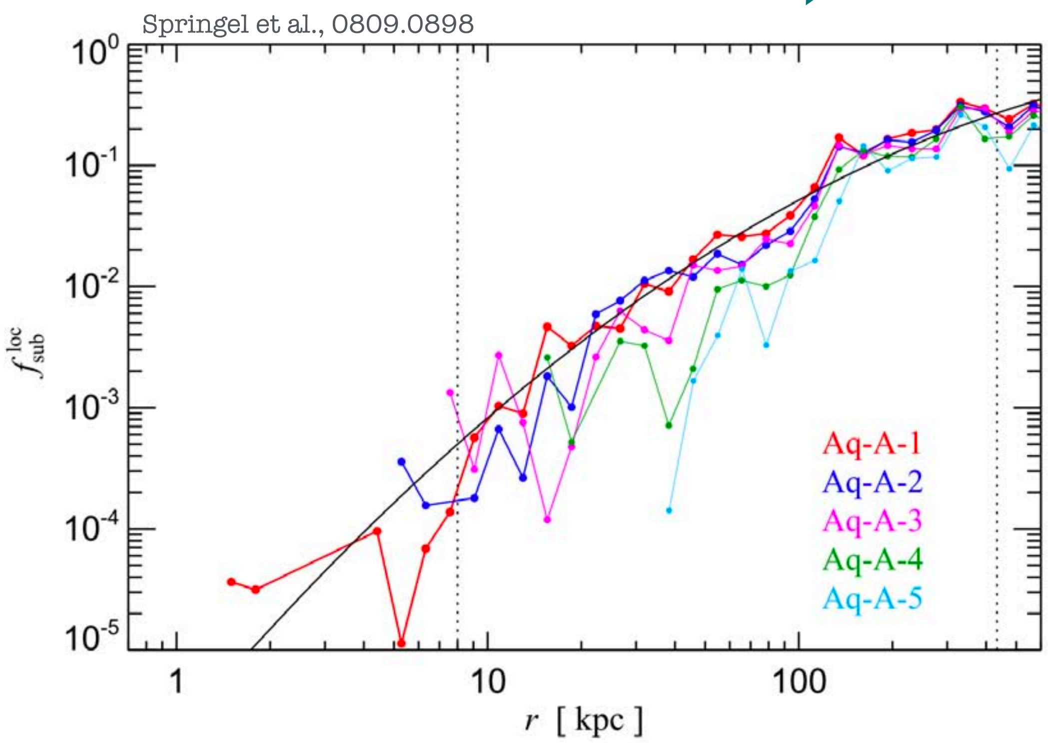
Spatial distribution inside the host halo

Can be coupled to the subhalo luminosity. **Work in progress!**

Otherwise, spatial distribution only interesting when sitting inside a halo



kDPDV_SPRINGEL08_ANTIBIASED	Springel et al. (2008): $\rho\,(r\,\vert\, r_{\rm e}, \rho_{\rm e}; \alpha) = \left(\frac{r}{r_{\rm e}}\right) \times \rho^{\rm EINASTO}(r, r_{\rm e}, \rho_{\rm e}, \alpha)$, with $r_{-2} = \left(\frac{3}{2}\right)^{1/\alpha} r_{\rm e}$. To use only to describe $\mathrm{d}\mathcal{P}_V/\mathrm{d}V$.
kDPDV_SPRINGEL08_FIT	Springel et al. (2008): $\frac{\bar\rho_{\rm sub}}{\bar\rho_{\rm tot}}(r\,\vert\, r_{50}; \alpha, \beta, \gamma) = \exp\left[\gamma + \beta \ln\left(\frac{r}{r_{50}}\right) + 0.5\alpha \ln^2\left(\frac{r}{r_{50}}\right)\right]$, Springel et al. (2008) use $\alpha = 0.36, \beta = 0.87, \gamma = 1.31$. To use only to describe $\mathrm{d}\mathcal{P}_V/\mathrm{d}V$.
kISHIYAMA14	Ishiyama (2014): NFW profile with a mass dependent inner slope $\gamma = -0.123 \log(M_{\rm vir}/10^{-6} M_\odot) + 1.461$ if $\alpha > 1$, or set to 1 otherwise. To use only to describe (subhalo) density profiles.

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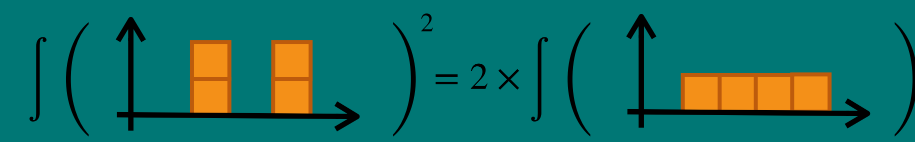
Annihilation boost in substructures



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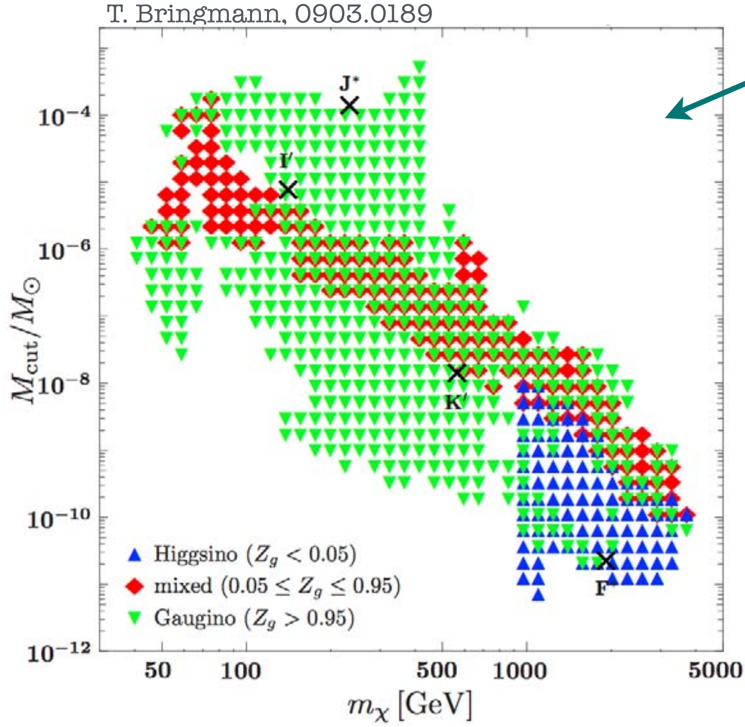
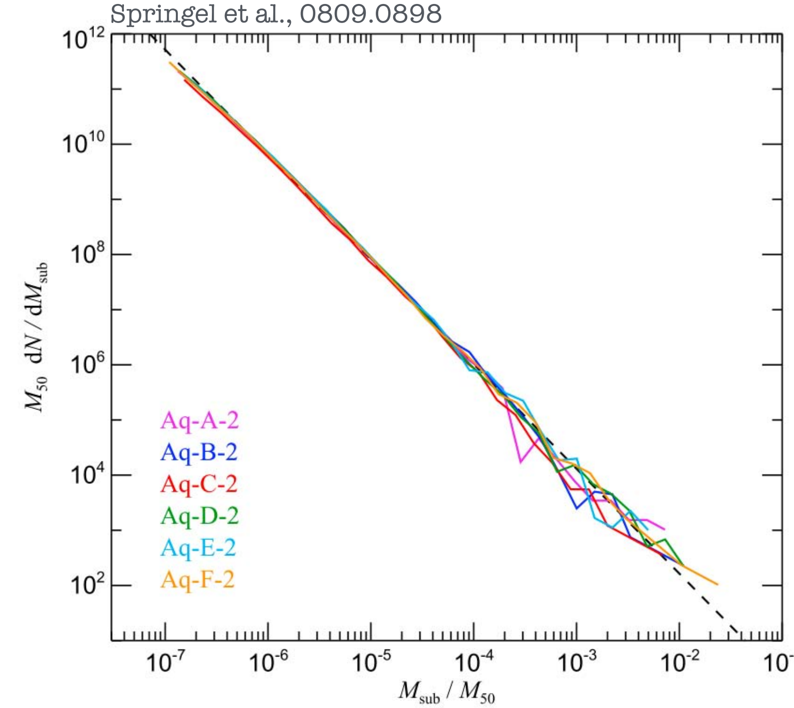
Minimal substructure mass dependent on DM particle mass

Large number of small-scale clumps

T. Bringmann, 0903.0189



Springel et al., 0809.0898



$$\frac{\mathrm{d}P_M}{\mathrm{d}M} \sim M^{-1.9}$$

While mass $\int_{M_{\rm min}}^{M_{\rm max}} M\,\frac{\mathrm{d}P_M}{\mathrm{d}M}\,\mathrm{d}M$ may well converge for $M_{\rm min}\to 0$, substructure boost may not

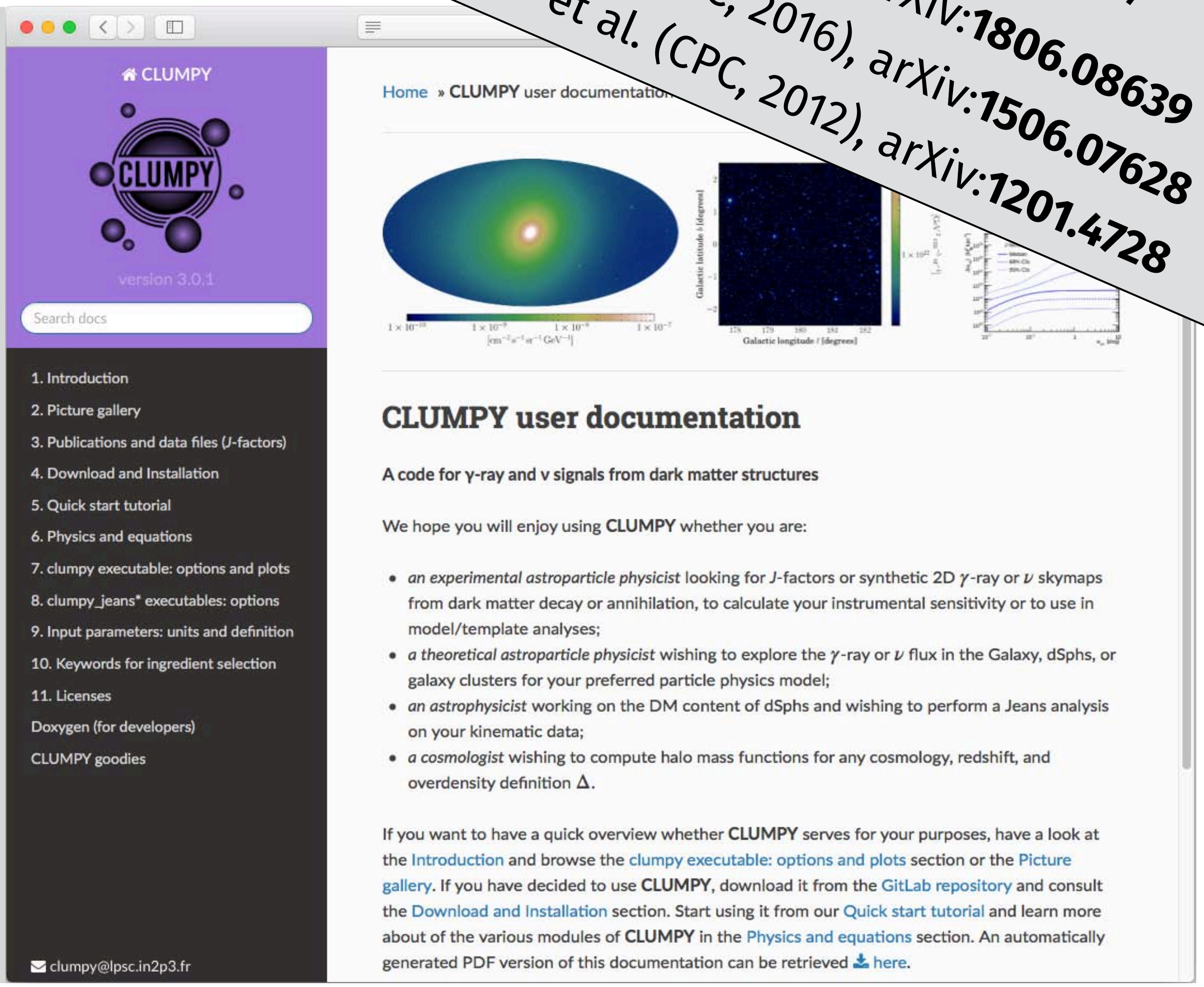
2. The code

```
if (is_simple_interp) printf("       ... Fill interpolation function (%d lin-steps) ...\n", n_base);
else printf("       ... Fill interpolation function (%d log-steps) ...\n", n_base);

j_1D_base.assign(n_base, 1.e-40);
phi_base.assign(n_base, 1.e-40);
iphi_inbase.assign(n_1D, -1);
double delta_phi_base;
if (is_simple_interp) delta_phi_base = (phi_max - phi_min) / double(n_base - 1);
else delta_phi_base = pow(phi_max / alpha_quad_start, 1. / double(n_base - 1));


for (int i = 0; i < n_base; ++i) {
   if (is_simple_interp) phi_base[i]  = phi_min + i * delta_phi_base;
   else phi_base[i] = alpha_quad_start * pow(delta_phi_base, i);
   double jopt = 1.e-40;
   if (switch_j == 0) {
      if (f_dm > 1.e-3)
         jopt = jsmooth_mix(mtot, par_tot, phi_base[i], theta_1D, lmin, lmax, eps, f_dm, par_dpdv);
      else
         jopt = jsmooth(par_tot, phi_base[i], theta_1D, lmin, lmax, eps);
   } else if (switch_j == 1) {
      // N.B.: we have to take into account all mass decades
      for (int k = 0; k < n_mass; ++k) {
         if (l_crit[k] < lmax)
            jopt += jsub_continuum(ntot_subs, par_dpdv, phi_base[i], theta_1D,
                                   l_crit[k], lmax,  par_subs, m1[k], m2[k]);
      }
   } else if (switch_j == 2) {
      // N.B.: we have to take into account all mass decades
      for (int k = 0; k < n_mass; ++k) {
         if (l_crit[k] < lmax)
            jopt += frac_nsubs_in_m1m2(&par_subs[8], m1[k], m2[k], gSIM_EPS)
                    * jcrossprod_continuum(mtot, par_tot, phi_base[i], theta_1D,
                                           l_crit[k], lmax, eps, f_dm, par_dpdv);
      }
   }
   if (jopt == 0.) jopt = 1.e-40;
   j_1D_base[i] = jopt;
}
// Set indices for phi_base[iphi_inbase] for phi_tab[i]
// Search (only once) for interpolation indices for angles
for (int i = 0; i < n_1D; ++i)
   iphi_inbase[i] = TMath::BinarySearch(n_base, &phi_base[0], phi_tab[i]);
}

if (is_interpolate) printf("       ... and interpolate for %d l.o.s. directions ...\n", n_1D);
```

What is CLUMPY?

https://lpsc.in2p3.fr/clumpy/
Hütten et al. (CPC, 2018), arXiv:**1806.08639**
Bonnivard et al. (CPC, 2016), arXiv:**1506.07628**
Charbonnier et al. (CPC, 2012), arXiv:**1201.4728**

- **Open-source** code, written in C/C++
- Public development on GitLab
- Depends on:
  - gsl
  - Heasarc's cfitsio
  - ~~HEALPix~~ (shipped with the code)
  - CERN's ROOT (optional)
  - GreAT (lpsc.in2p3.fr/great, optional)
- Runs on **Linux** and **MacOS X**
- **Extensive web documentation**

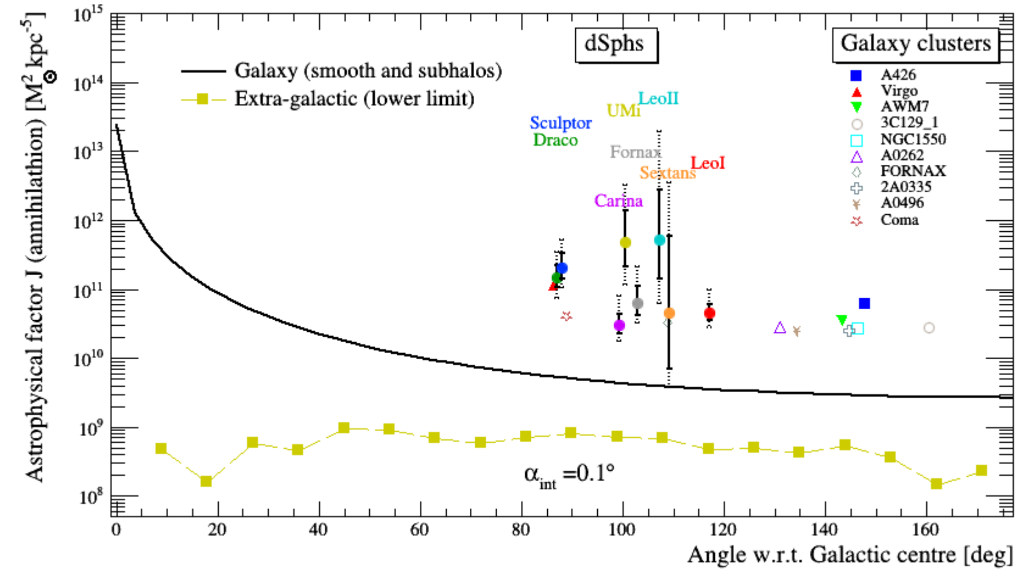


Open source code to provide the community with reproducible and comparable models for J-factors and prompt γ-ray/ν fluxes

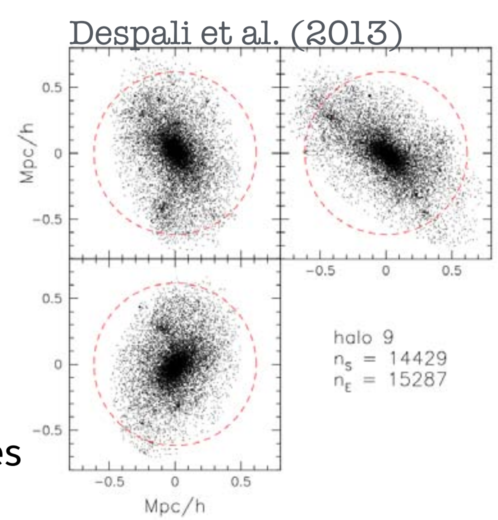
CLUMPY features (I): $\rho_{\rm sm} + \rho_{\rm subs} \rightarrow J$-factor/flux

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

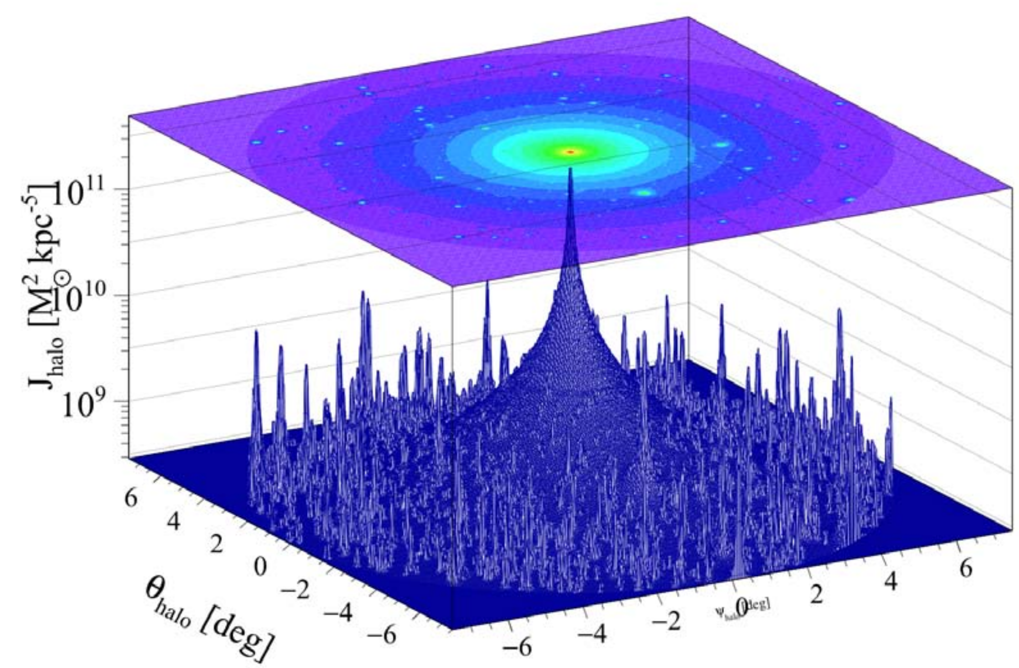
- Propagate **error bars from DM profiles to J-factors and limits on DM**
  (Bonnivard ApJ, MNRAS, 2015)
- Take into account **substructures**:
  - resolved (statistical) + unresolved: **boost**
  - vary distribution within host halo (antibiased, own profile,...)
  - Clumps within clumps: multiple levels 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
(Charbonnier et al., MNRAS, 2011; Nezri et al., MNRAS, 2012)



N-body simulations/kinematic analyses find triaxial halo shapes



LMC $\mathrm{d}J/\mathrm{d}\Omega$ profile with resolved substructure model (analysis done by M. Castaño, São Paulo)

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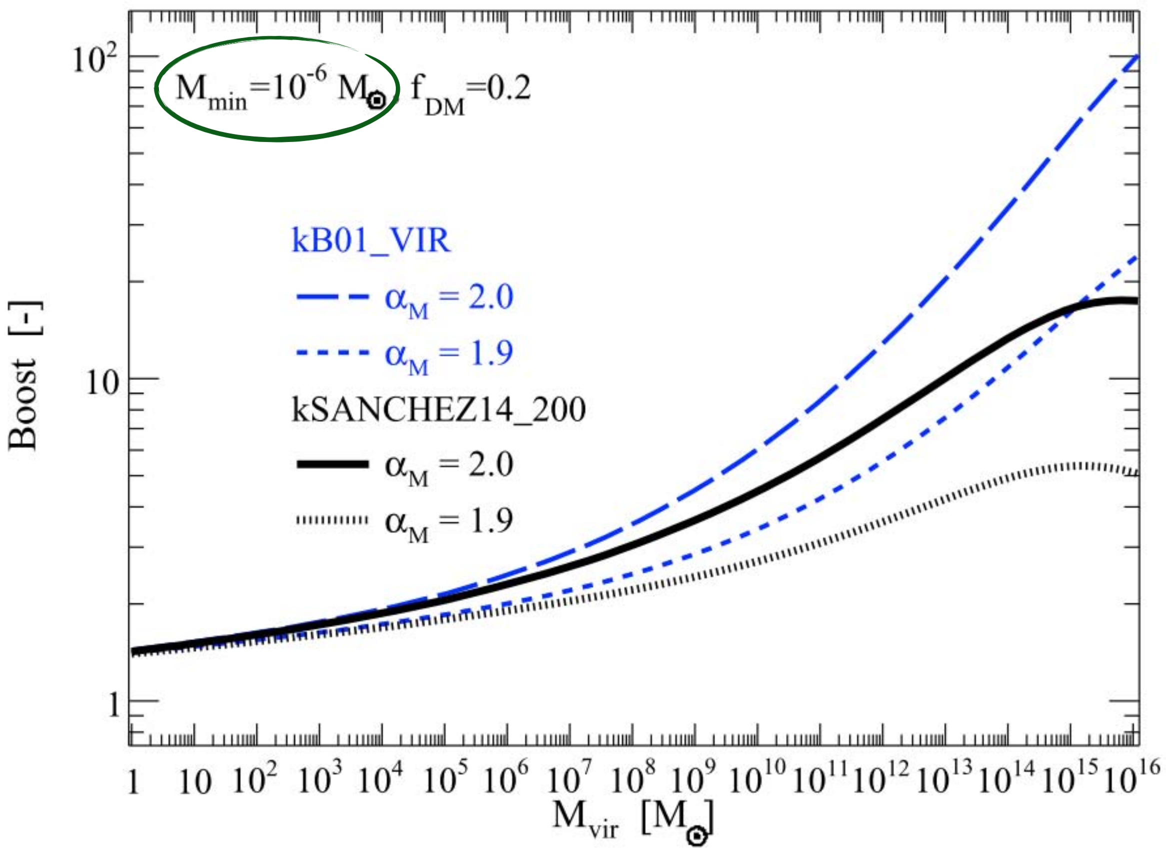
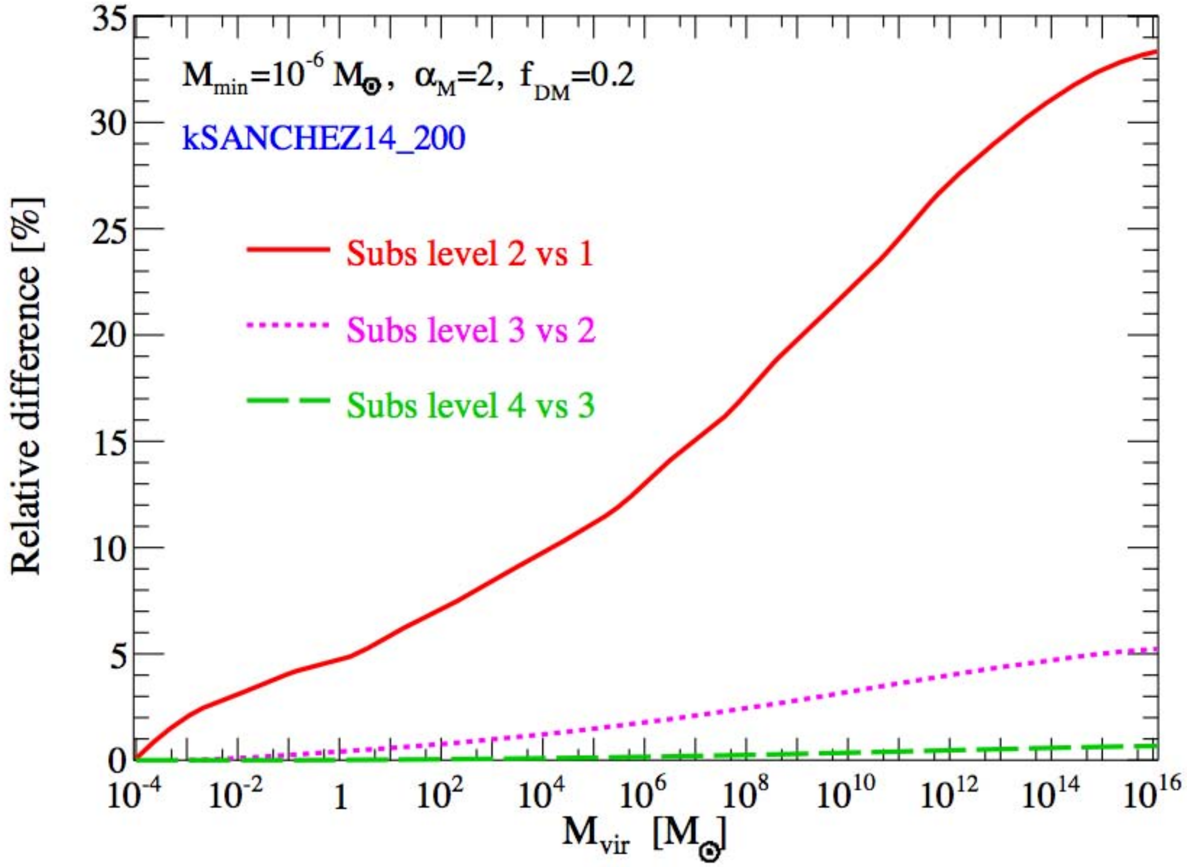
Some results: Boost uncertainty (Bonnivard et al., 1506.07628)

Boost from different $\left\langle \frac{dJ_{sub}}{d\Omega}(\theta) \right\rangle$ models



dSph: $\mathrm{boost}(\theta) \sim 1 - 2$
Galaxy cluster: $\mathrm{boost}(\theta) \sim 10 - 100$?

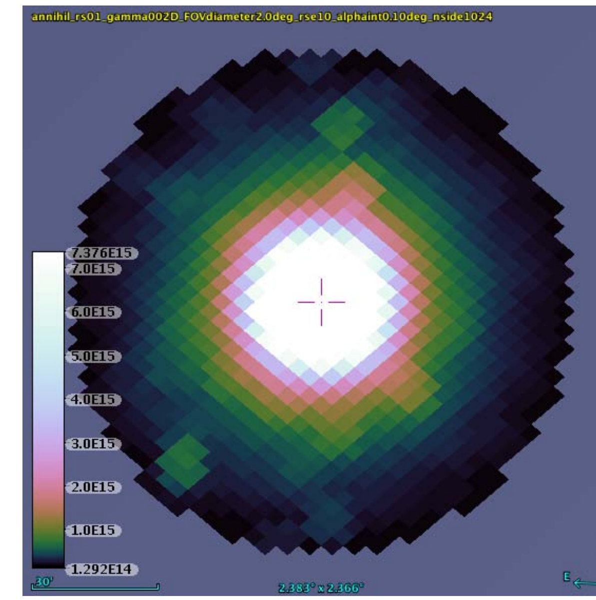
Also consider self-similar sub-subclustering



CLUMPY features (I): $\rho_{\rm sm} + \rho_{\rm subs} \rightarrow J$-factor/flux

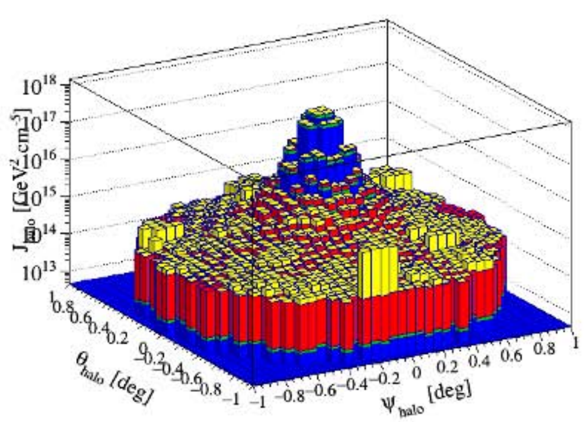
J-factors/fluxes of individual objects (e.g. dSph's) from **pre-defined DM profiles**

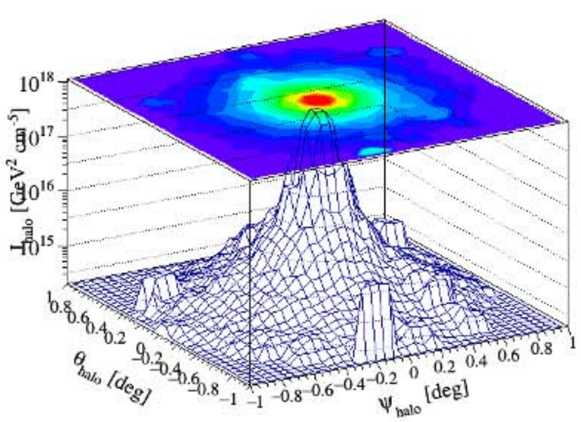
- ROOT **pop-up graphics** (1D and 2D)
- 2D images smoothable with Gaussian beam,
- **Choose output format**: ROOT, HEALPix FITS (2D), ASCII
- FITS images **interfaceable with gammalib/**



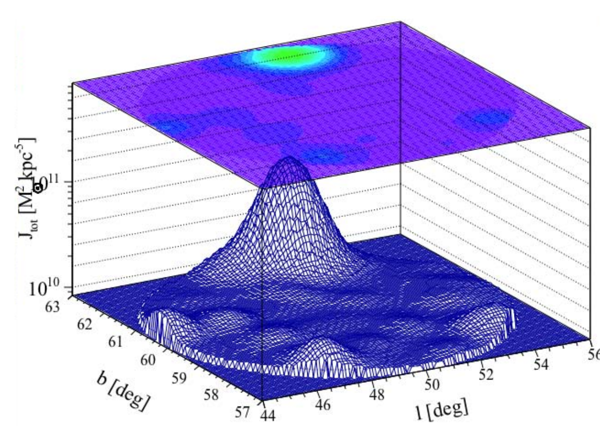
HEALPix pixelization (FITS format)

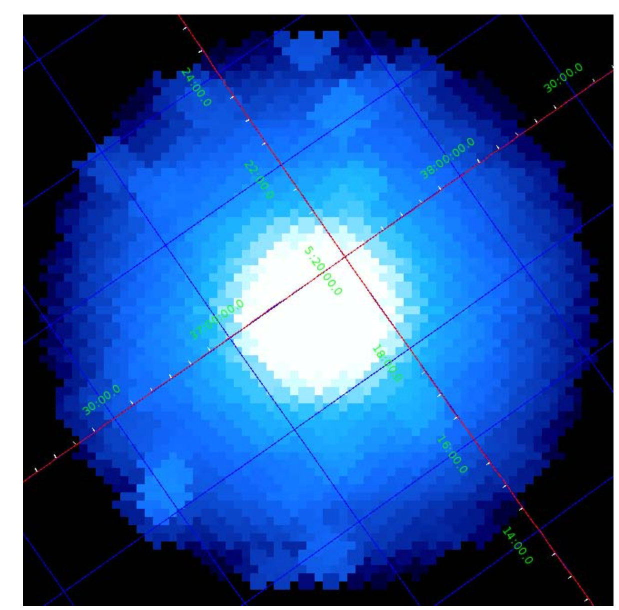
ROOT plots and output format





Smoothing with Gaussian beam





projected FITS image

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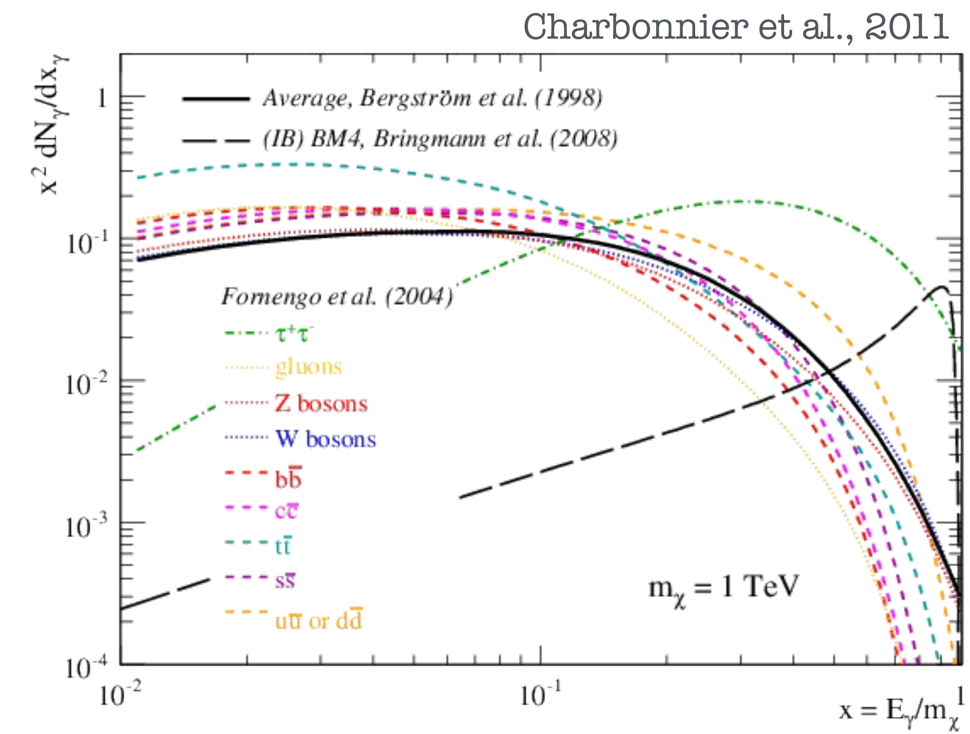
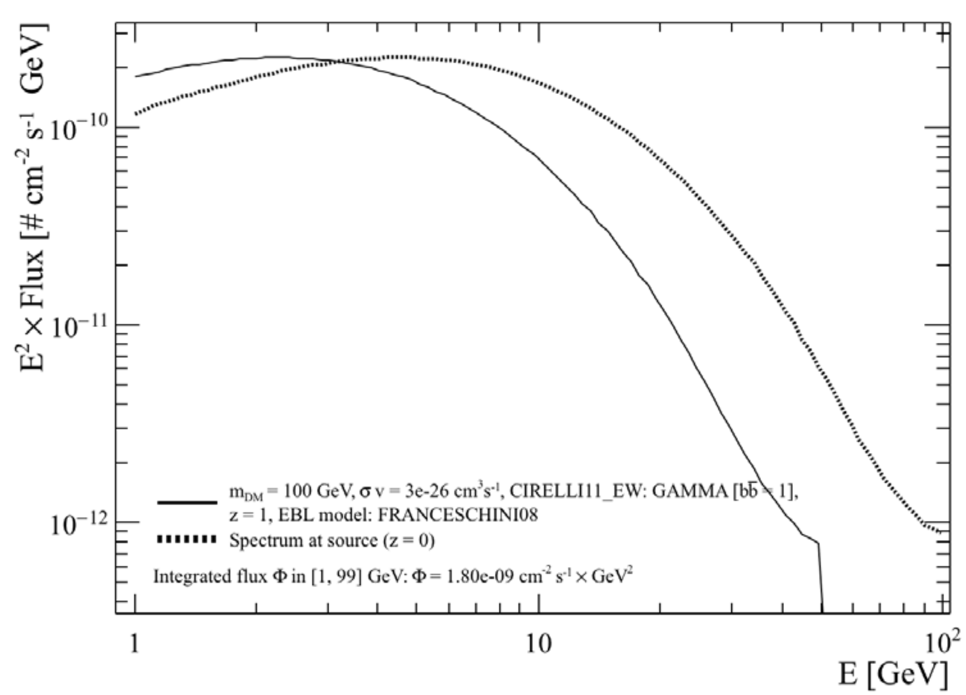
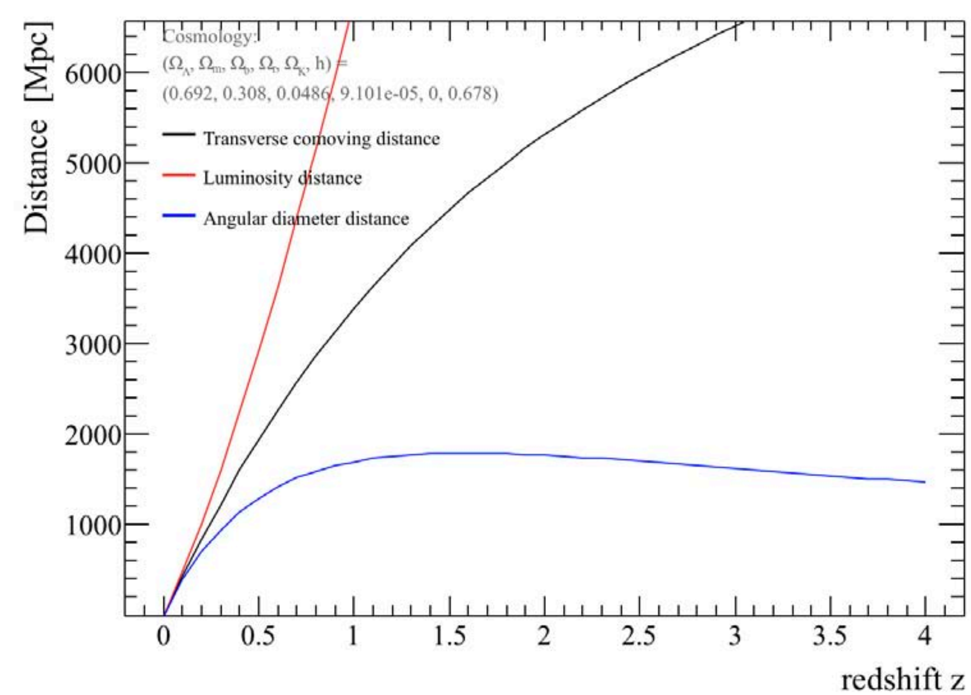
CLUMPY features (I): $\rho_{\rm sm} + \rho_{\rm subs} \rightarrow J$-factor/flux

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

- Directly **compute differential/integral fluxes** (1D and 2D), relying on PPPC4DMID (Cirelli et al., 2010)
- **Correct cosmology** (line-of-sight and angular diameter distance) + **EBL flux absorption** for extragalactic objects



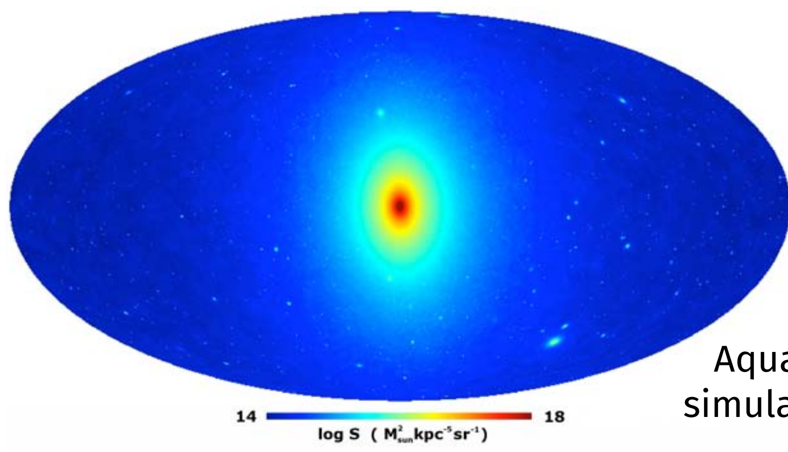


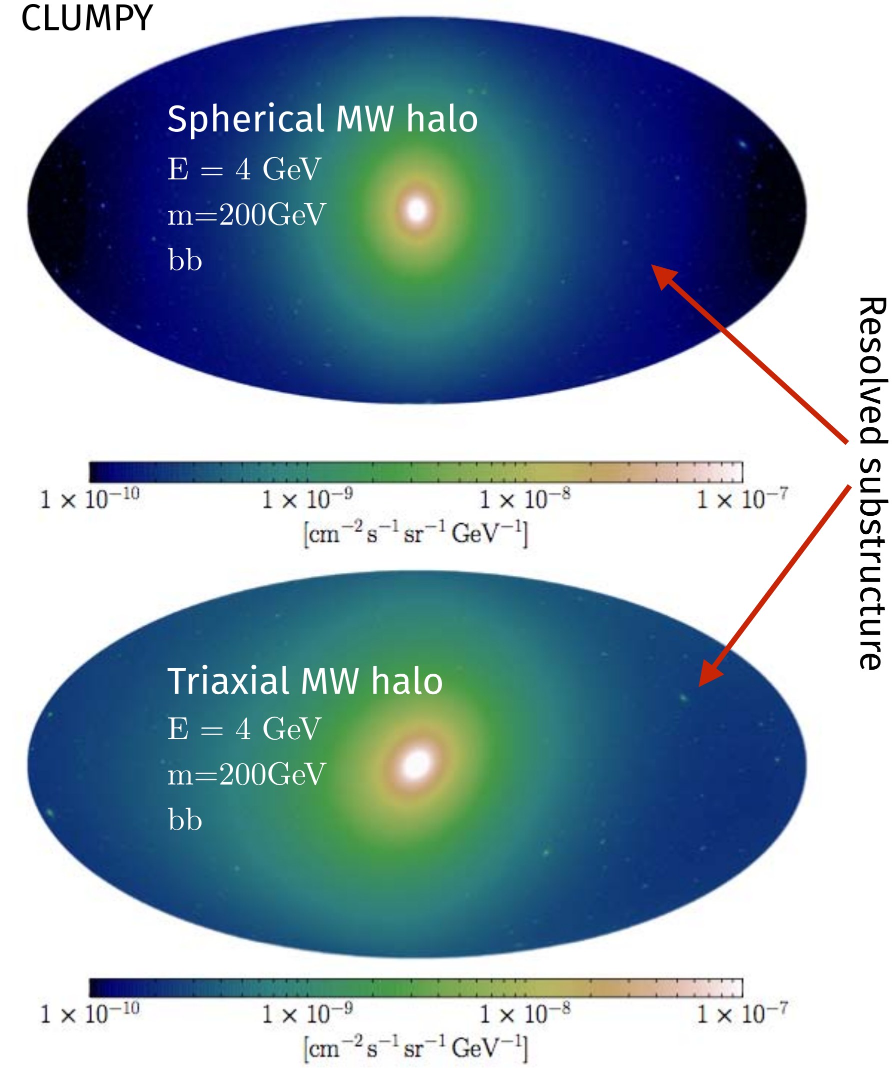


CLUMPY features (II): Full-sky MW analysis with subhalos

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

- Fast realistic synthetic skymaps at any instrumental resolution
  - 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
  - Pre-select brightest subhalos for speed (e.g., reduce 10^{15} total subhalos in the MW to $\sim 10^4$ at a precision of 2% and $\theta_{\rm int} = 0.2°$).
  - allow statistical assessment of MW substructure properties (average mass, distance, luminosity,...)





Hütten et al., JCAP (2016)

CLUMPY features (III): Jeans analysis module

From stellar kinematics to DM profile

Data

- Light profile & velocity dispersion

$I(R)$ — de-projection → ν stellar density

$\sigma_p^2(R)$ ← projection — $\bar{v}_r^2$ radial velocity dispersion

stellar density & radial velocity dispersion

Gravitation

- Spherical Jeans equation: solve for $\bar{v}_r^2$

$$\frac{1}{\nu}\frac{\mathrm{d}\left(\nu \bar{v}_r^2\right)}{\mathrm{d}r} + \frac{2\,\beta_{\rm ani}\,\bar{v}_r^2}{r} = -\frac{G\,M(r)}{r^2}$$

$\beta_{\rm ani} = 1 - \bar{v}_\theta^2/\bar{v}_r^2$: anisotropy

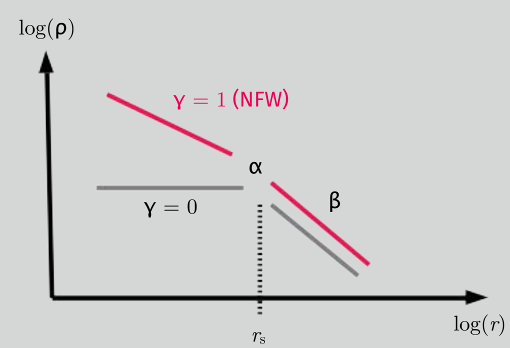
$$M(r) = 4\pi \int_0^r \rho(r')\, r'^2\, \mathrm{d}r'$$

enclosed mass

DM model

- Dark matter profile

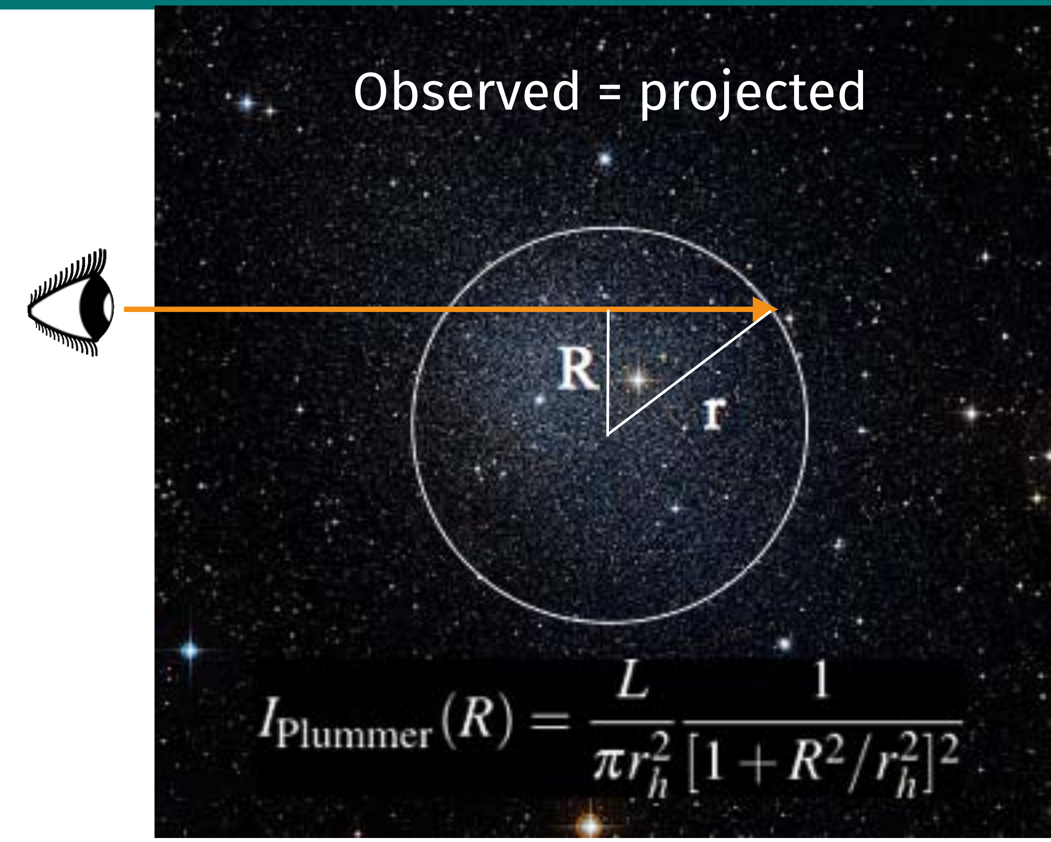
$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^\gamma \left[1 + \left(\frac{r}{r_s}\right)^\alpha\right]^{(\beta-\gamma)/\alpha}}$$



Fit

- χ^2 or MCMC analysis to extract DM parameters

$\rho_s,\ r_s,\ \alpha,\ \beta,\ \gamma,$ and $\beta_{\rm ani}$



CLUMPY features (III): Jeans analysis module

- Modelling light profile and anisotropy profile:

Abel-transformed projected Jeans equation:

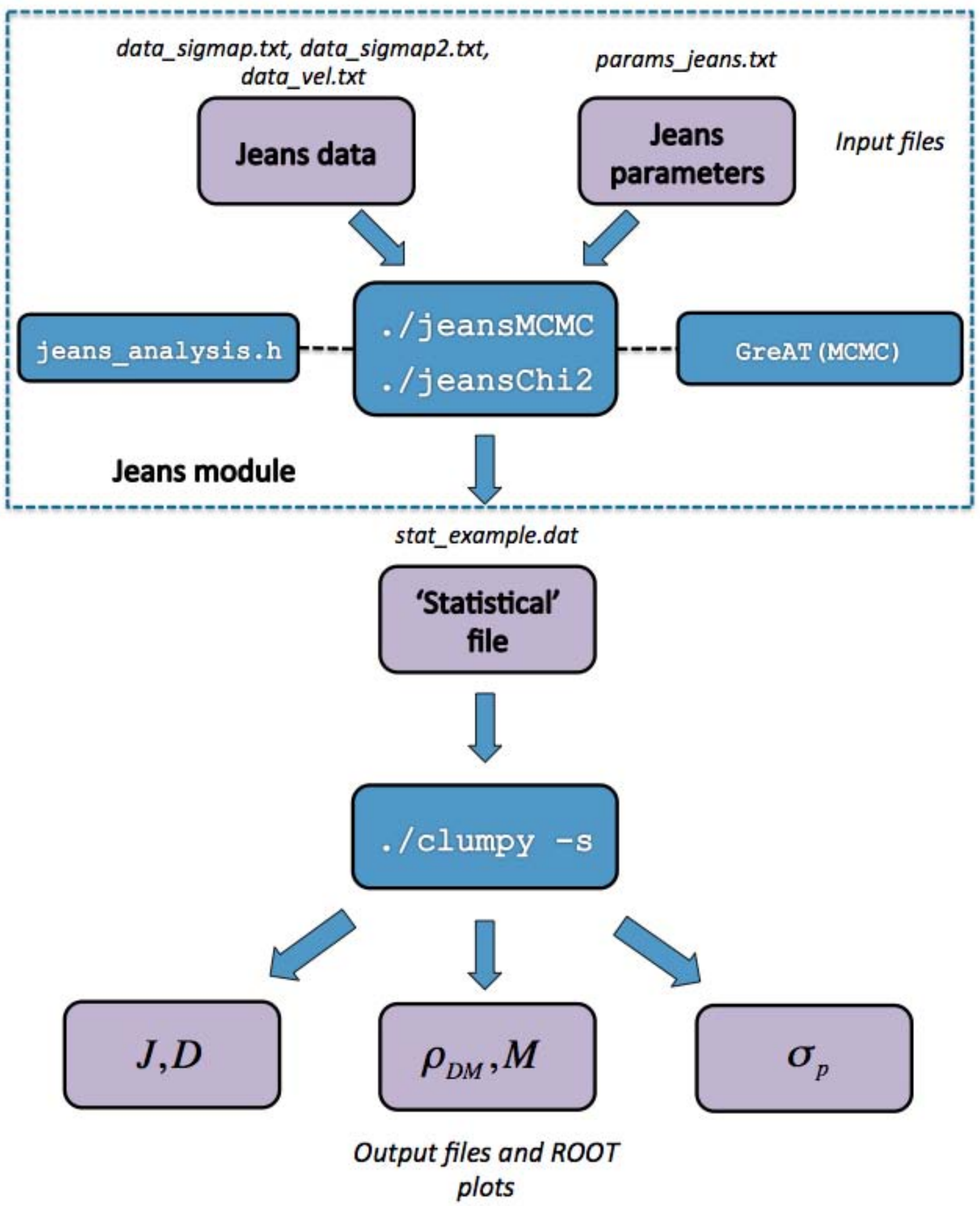
$$I(R)\sigma_p^2(R) = 2\int_R^\infty \left(1-\beta_{\rm ani}(r)\frac{R^2}{r^2}\right)\frac{\nu(r)\,\bar{v_r^2}(r)\,r}{\sqrt{r^2-R^2}}\,{\rm d}r$$
$$= 2\int_0^\infty \left(1-\beta_{\rm ani}(r)\frac{R^2}{r^2}\right)\nu(r)\,\bar{v_r^2}(r){\rm d}y.$$

Keyword	Surface brightness $\Sigma(R)\equiv I(R)$		Density profile $\rho(r)\equiv\nu(r)$	# free param.	References
kEXP2D	$\Sigma_0\times\exp(-\frac{R}{r_c})$	→	$\frac{\Sigma_0}{\pi r_c}\times K_0\left(\frac{r}{r_c}\right)$	2	Evans, An, and Walker (2009)
kEXP3D	$2\rho_0\,R\times K_1\left(\frac{R}{r_c}\right)$	←	$\rho_0\times\exp(-\frac{r}{r_c})$	2	Evans, An, and Walker (2009)
kKING2D	$\Sigma_0\times\left[\left(1+\frac{R^2}{r_c^2}\right)^{-1/2} -\left(1+\frac{r_{\rm lim}^2}{r_c^2}\right)^{-1/2}\right]^2$	→	$\frac{\Sigma_0}{\pi r_c}\times\frac{\cos^{-1}(z)/z-\sqrt{1-z^2}}{z^2(1+r_{\rm lim}^2/r_c^2)^{3/2}}$ with $z^2=\frac{1+r^2/r_c^2}{1+r_{\rm lim}^2/r_c^2}$	3	King (1962), Strigari et al. (2008)
kPLUMMER2D	$\frac{\Sigma_0}{\pi r_c^2}\times\left(1+\frac{R^2}{r_c^2}\right)^{-2}$	→	$\frac{3\Sigma_0}{4\pi r_c^3}\times\left(1+\frac{r^2}{r_c^2}\right)^{-5/2}$	2	Plummer (1911), Evans et al. (2009)
kSERSIC2D	$\Sigma_0\times\exp\left\{-b_n\left[\left(\frac{R}{r_c}\right)^{\frac{1}{n}}-1\right]\right\}$ with $b_n=2n-1/3+0.009876/n$	→	$-\frac{1}{\pi}\int_r^\infty\frac{{\rm d}\Sigma(R)}{{\rm d}R}\times\frac{{\rm d}R}{\sqrt{R^2-r^2}}$	3	Sérsic (1968), Prugniel & Simien (1997), Graham and Driver (2005), Merritt et al. (2006)
kZHAO3D	$2\int_R^\infty\rho(r)\,r\times\frac{{\rm d}r}{\sqrt{r^2-R^2}}$	←	$\rho_0\times\frac{(r/r_s)^{-\gamma}}{\left[1+\left(\frac{r}{r_s}\right)^\alpha\right]^{(\beta-\gamma)/\alpha}}$	5	Hernquist (1990), Zhao (1996)

Keyword	Anisotropy $\beta_{\rm anis}(r)$	$f(r)$ to solve Eq. (6.10) $=\nu(r)\bar{v_r^2}(r)$
kCONSTANT	β_0	$r^{2\beta_0}$
kBAES	$\frac{\beta_0+\beta_\infty(r/r_a)^\eta}{1+(r/r_a)^\eta}$	$r^{2\beta_0}\left[1+\left(\frac{r}{r_a}\right)^\eta\right]^{2(\beta_\infty-\beta_0)/\eta}$
kOSIPKOV	$\frac{r^2}{r^2+r_a^2}$ (special case of kBAES)	$\frac{r_a^2+r^2}{r_a^2}$

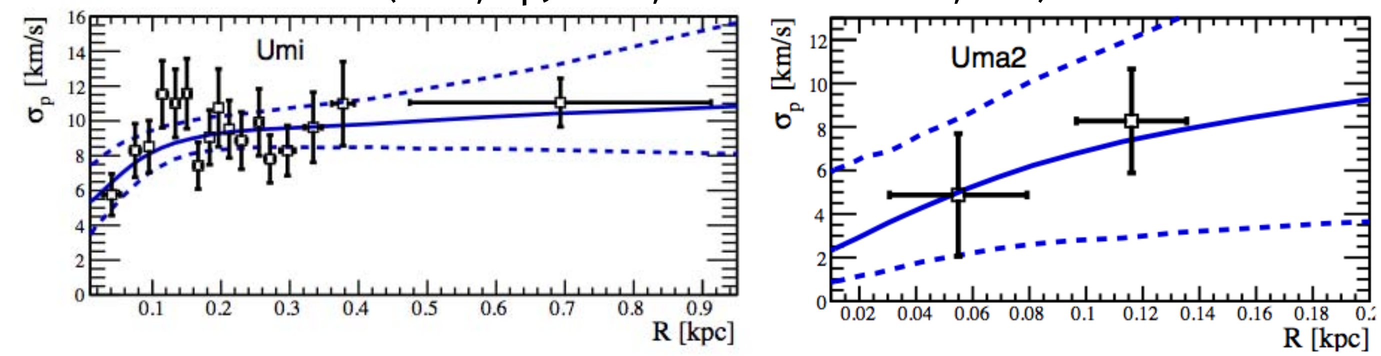
CLUMPY features (III): Jeans analysis module

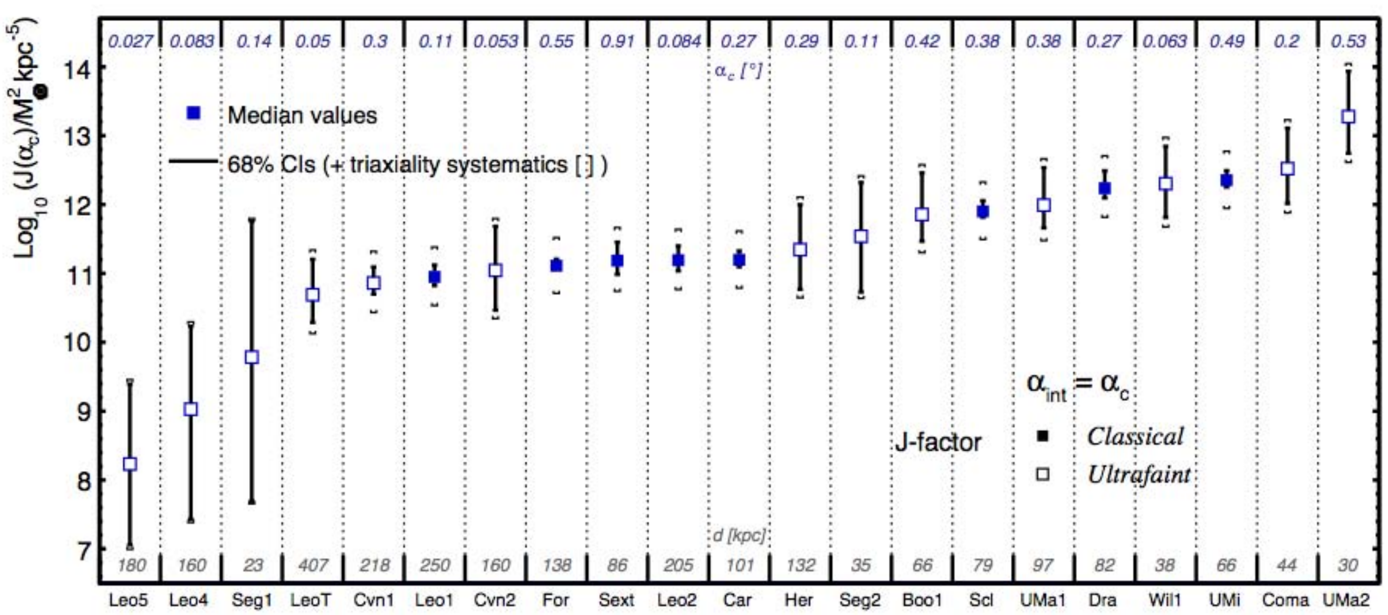
Dsph galaxy analysis: ranking and/or credible intervals



CLUMPY modules I + III together

Bonnivard et al. (2015, ApJL 808, 36 + MNRAS 453, 849)

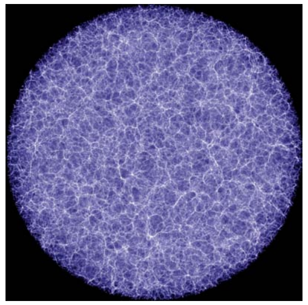




Many new MW satellite galaxies just discovered (DES) & expected (e.g., LSST): CLUMPY can be used as soon as spectroscopic data is available

CLUMPY features (IV): Extragalactic diffuse intensity

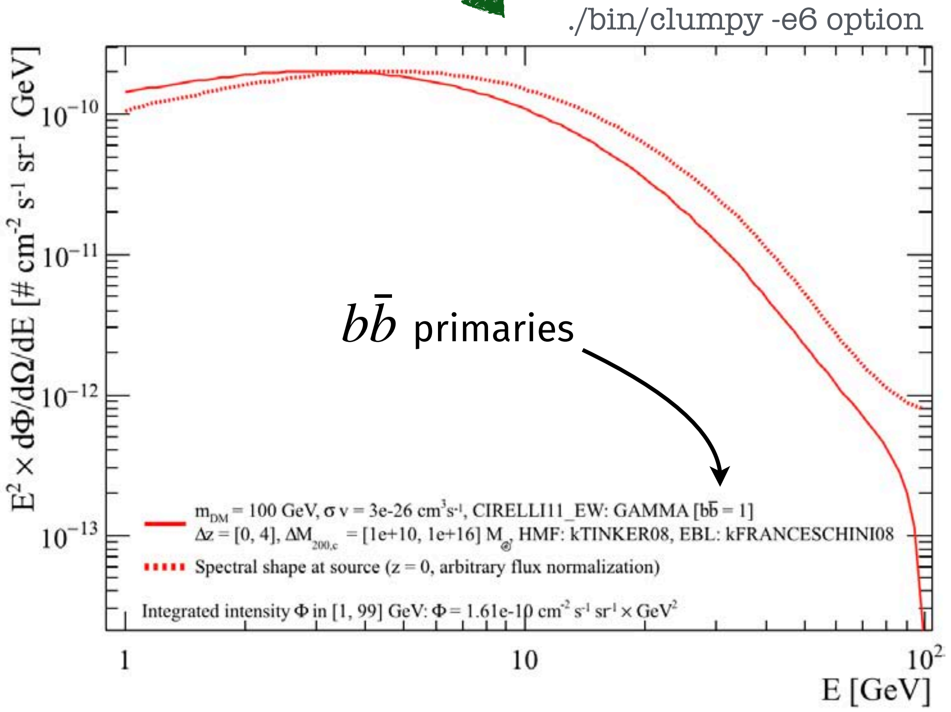
$$\left\langle \frac{\mathrm{d}\Phi}{\mathrm{d}E_{\mathrm{obs}}\,\mathrm{d}\Omega} \right\rangle_{\mathrm{sky}} = \frac{\overline{\varrho}^{2}_{\mathrm{DM},0}\,\langle\sigma v\rangle}{4\pi\,\delta\,m_\chi^2} \int_0^{z_{\max}} c\,\mathrm{d}z\,\frac{(1+z)^3}{H(z)} \left\langle \delta^2(z) \right\rangle \frac{\mathrm{d}N_\nu}{\mathrm{d}E_{\mathrm{source}}}\Bigg|_{E_{\mathrm{source}}=(1+z)E_{\mathrm{obs}}}$$



Intensity multiplier

$$\left\langle \delta^2(z) \right\rangle = \frac{1}{\overline{\varrho}^{2}_{\mathrm{m},0}} \int \mathrm{d}M\,\frac{\mathrm{d}n}{\mathrm{d}M}(M,z) \times \mathscr{L}(M,z)$$

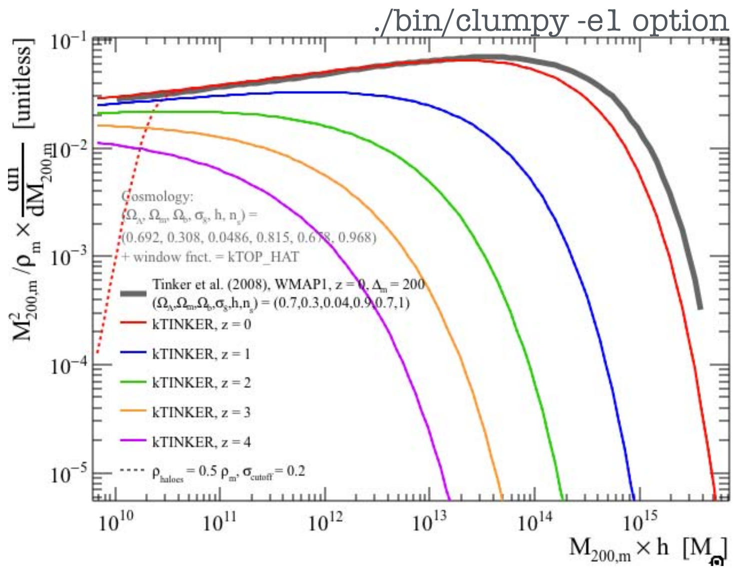
Redshifting of spectrum

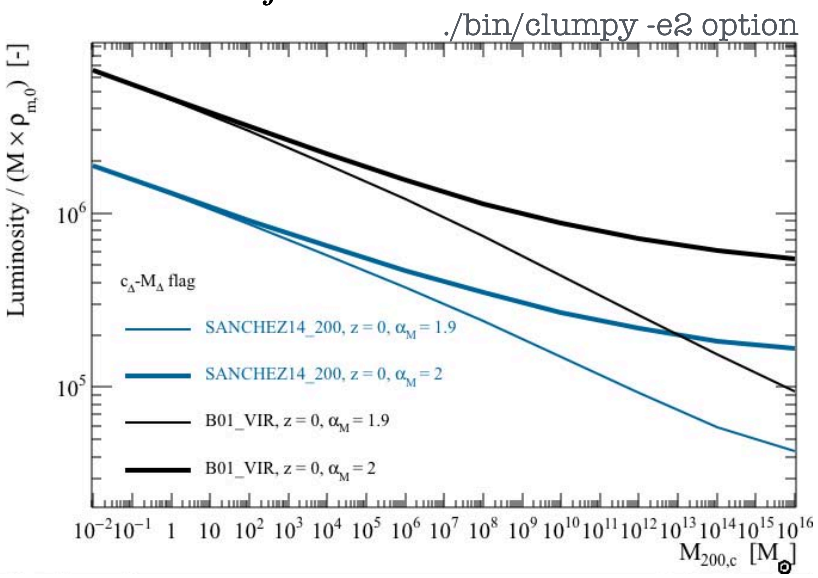


Halo mass function

One-halo luminosities

$$\mathscr{L} = \int \mathrm{d}V\,\rho^2_{\mathrm{halo}}$$





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Summary

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

- Code distribution and usage:
  - Open-source: reproducible and comparable J-factor calculations
  - User-friendly Sphinx documentation, 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
  - Boost from substructures and its uncertainty
  - 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

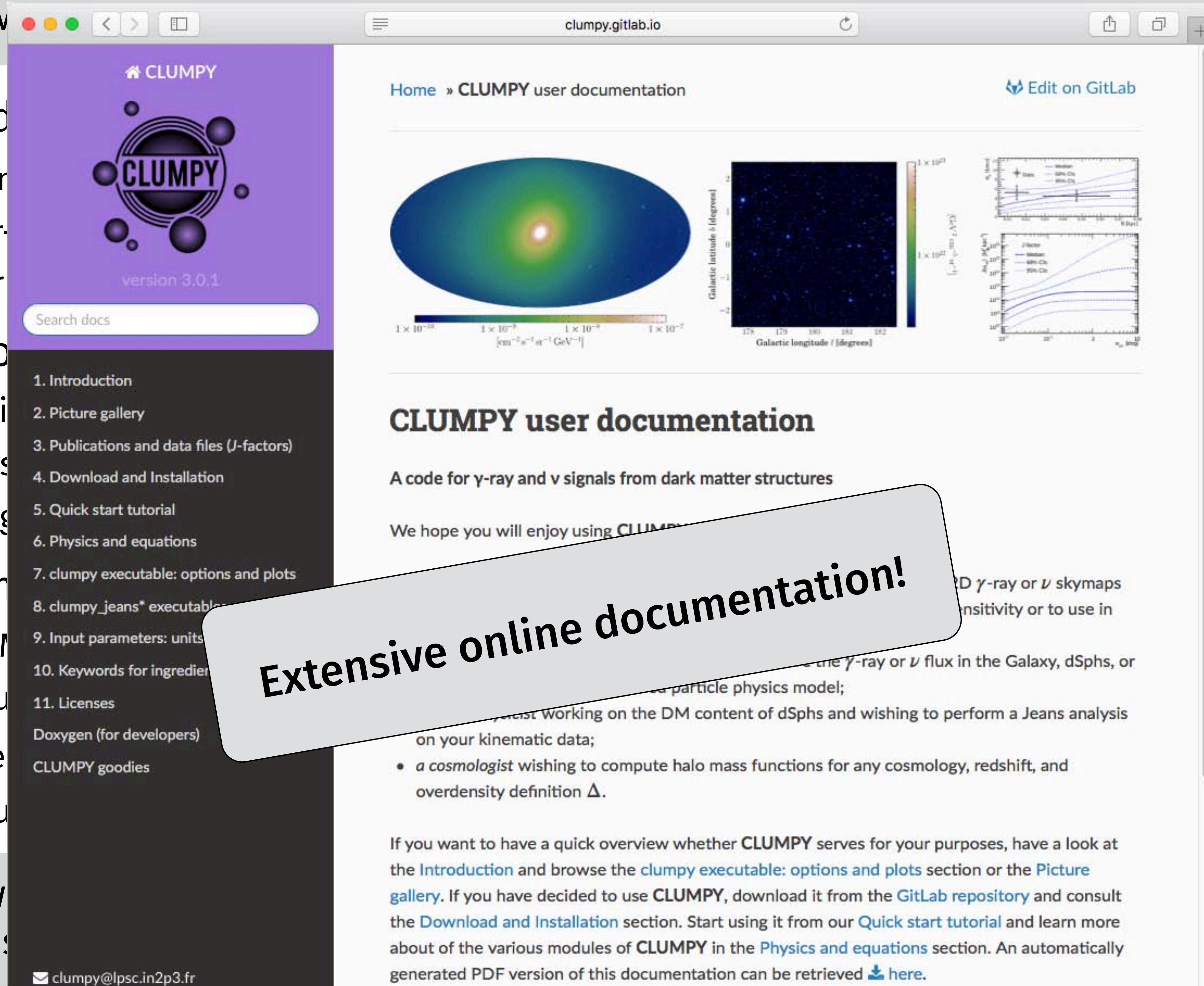
Growing use in the community for state-of-the-art DM studies for many targets (dSphs, cluster, dark clumps...) and by various collaborations (MAGIC, CTA, HAWC)

Download from **https://lpsc.in2p3.fr/clumpy/**

Summary

CLUM… …lysis

- Code d…
  - Oper…
  - User…
  - All r…
- Fast co…
  - Anni…
  - Boos…
  - Integ… …ratios
- Four m…
  - I. DM
  - II. Fu… …s from list
  - III. Je…
  - IV. Fu…



Grow… …rgets
(dSph… …HAWC)

Download from https://lpsc.in2p3.fr/clumpy/

All parameters controlled from parameter file

Name	Definition
Cosmological parameters (updated from Planck results)	
gCOSMO_HUBBLE	Hubble expansion rate $h = H_0/(100\ \mathrm{km\ s^{-1}\ Mpc^{-1}})$ [-]
gCOSMO_RHO0_C	Critical density of the universe [$M_\odot\ \mathrm{kpc}^{-3}$]
gCOSMO_OMEGA0_M	Present-day pressure-less matter density
gCOSMO_OMEGA0_LAMBDA	Present-day dark energy density
Dark matter parameters	
gDM_FLAG_CVIR_DIST	Distribution around $\bar{c}(M)$ from which concentrations are drawn: {kLOGNORM, kDIRAC}
gDM_LOGCVIR_STDDEV	Width of log-normal $c(M)$ distribution (if gDM_FLAG_CVIR_DIST=kLOGNORM)
gDM_SUBS_NUMBEROFLEVELS	Number of levels for subhaloes
gDM_MMIN_SUBS	Minimal mass of DM haloes [$M_\odot$]
gDM_MMAXFRAC_SUBS	Defines the maximal mass of clump in host halo: $M_{\rm max}$ = gDM_MMAXFRAC_SUBS $\times M_{\rm host}$
gDM_RHOSAT	Saturation density for DM [$M_\odot\ \mathrm{kpc}^{-3}$]
Generic (sub-)halo structural parameters (TYPE = DSPH, GALAXY or CLUSTER)	
gTYPE_CLUMPS_{FLAG_PROFILE, ...}	Description of subhaloes for host TYPE: $c(M)$, inner profile, shape parameters
gTYPE_DPDM_SLOPE	Slope of the clump mass function
gTYPE_DPDV_{FLAG_PROFILE, RSCALE, ...}	Spatial distribution of substructures in object TYPE
gTYPE_SUBS_MASSFRACTION	Mass fraction of the host halo in clumps
Milky-Way DM (sub-)halo structural parameters	
gGAL_CLUMPS_{FLAG_PROFILE, ...}	Description of Milky-way DM subhaloes
gGAL_DPDM_SLOPE	Slope of clump mass function
gGAL_DPDV_{FLAG_PROFILE, RSCALE, ...}	Spatial distribution of substructures in object TYPE
gGAL_SUBS_{M1, M2, N_INM1M2}	Number of Milky-Way subhaloes in [M_1, M_2]
gGAL_{RHOSOL, RSOL, RVIR}	Local DM density [GeV cm^{-3}], distance GC–Sun [kpc], virial radius [kpc]
gGAL_TOT_{FLAG_PROFILE, RSCALE, ...}	Description of the total DM profile
gGAL_TRIAXIAL_AXES[0-3]	Dimensionless major (a), intermediate (b), and minor (c) axes (see Eq. (18))
gGAL_TRIAXIAL_ROTANGLES[0-3]	Euler rotation angles for triaxial Milky-Way halo [deg]
gGAL_TRIAXIAL_IS	Switch-on or off triaxiality calculation (i.e., use or not the 2 parameters above)

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All parameters controlled from parameter file

Particle physics ingredients (for γ-ray and ν flux calculation)

gPP_BR[gN_PP_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 $\tau_{\rm DM}$ 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 $m_{\rm DM}$ 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	DM haloes considered in J-factor calculations [default=data/list_generic.txt]
gLIST_HALOES_JEANS	Objects considered in Jeans's analysis [default=data/list_generic_jeans.txt]
gSIMU_ALPHAINT_DEG	Integration angle $\alpha_{\rm int}$ [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 γ-ray detector for skymaps smoothing (no smoothing if set to -1)
gSIMU_GAUSSBEAM_NEUTRINO_FWHM_DEG	Gaussian beam [deg] for ν detector for skymaps smoothing (no smoothing if set to -1)
gSIMU_HEALPIX_NSIDE	$N_{\rm side}$ of HEALPix maps (if -1, set to be as close as possible to $\alpha_{\rm int}$)
gSIMU_HEALPIX_RING_WEIGHTS_DIR	Ring weights directory for improved quadrature (optional)
gSIMU_IS_ASTRO_OR_PP_UNITS	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 γ-ray and ν fluxes (the J factor is always saved)
gSIMU_IS_WRITE_FLUXMAPS_INTEG_OR_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)