CLUMPY: A public code for neutrino fluxes from dark matter structures at all scales

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for the CLUMPY developers:
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Dark Ghosts workshop Brussels, Nov. 14 2018

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

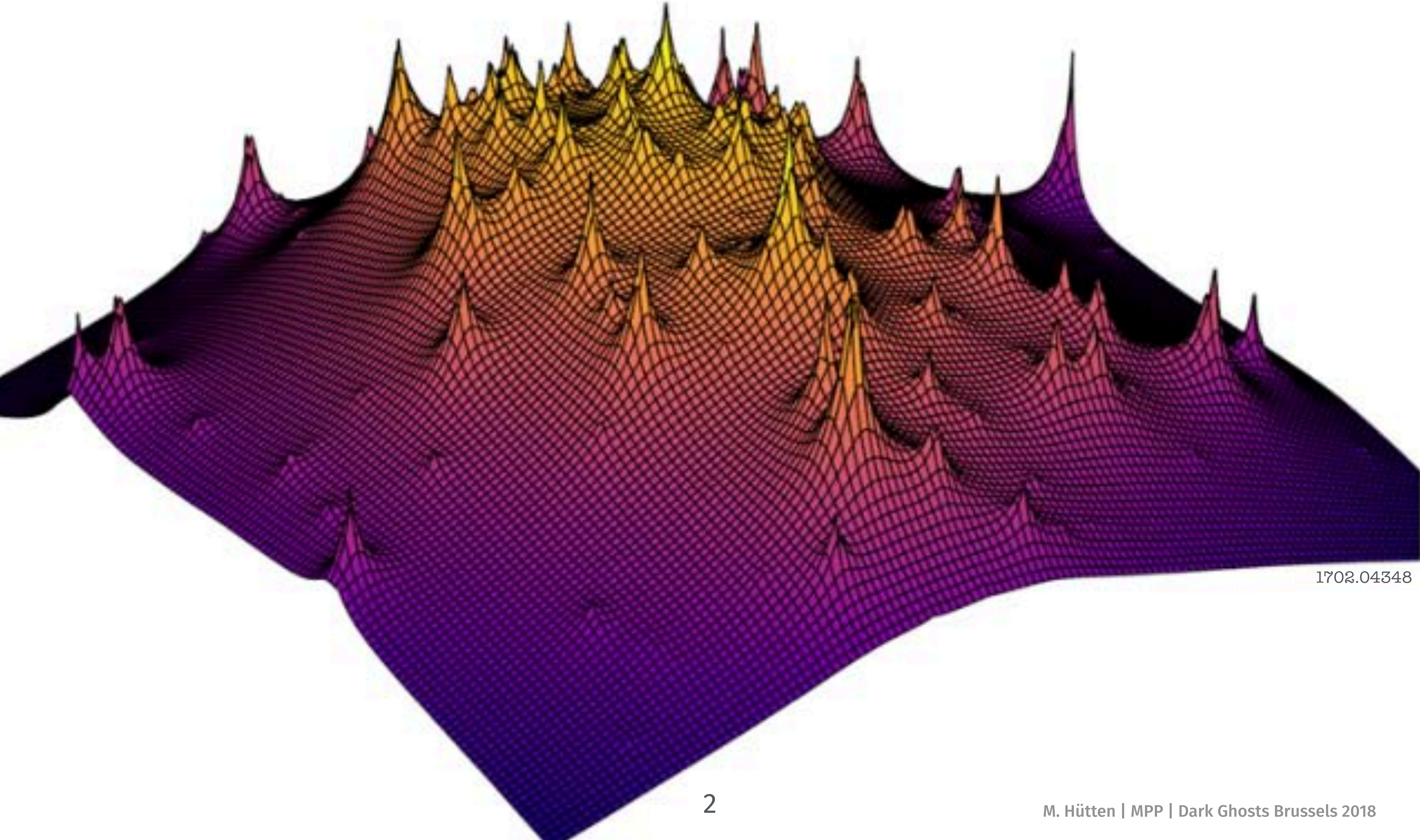
Hütten et al. (CPC, 2018), arXiv:**1806.08639**
Bonnivard et al. (CPC, 2016), arXiv:**1506.07628**
Charbonnier et al. (CPC, 2012), arXiv:**1201.4728**

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Enigmass

Dark Ghosts Brussels, 13-14 November 2018
2nd GNN Workshop on Indirect Dark Matter Searches with Neutrino Telescopes

1. Introduction - physics problem



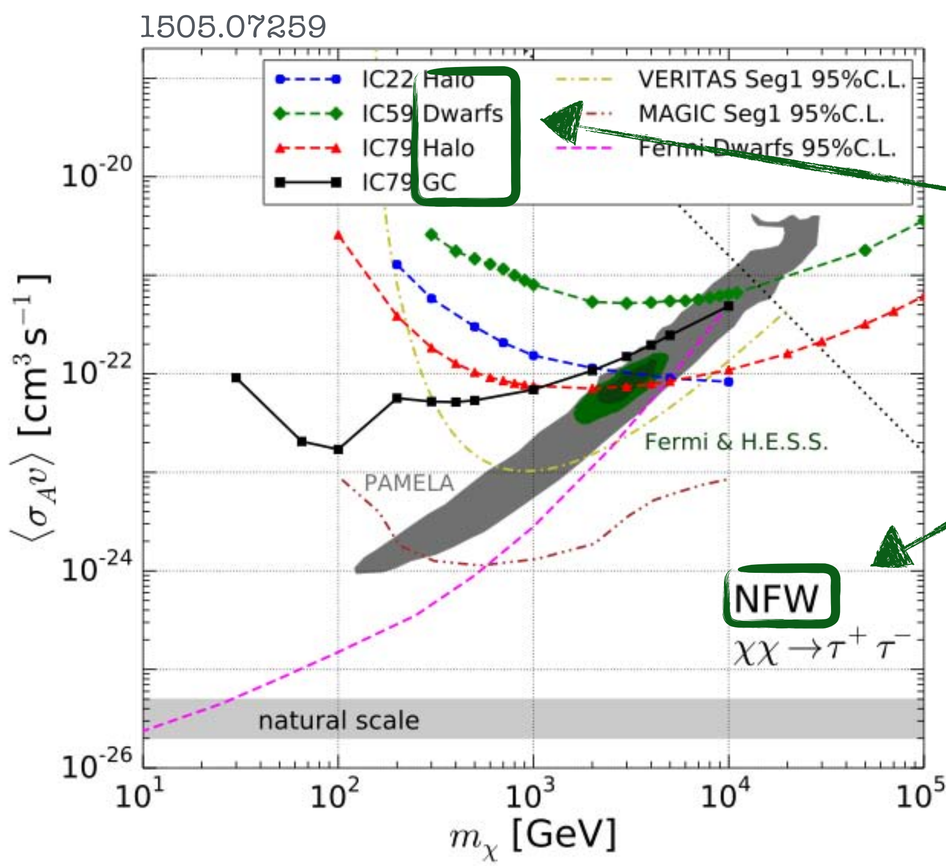
1702.04348

Indirect DM detection in neutral particles

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

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

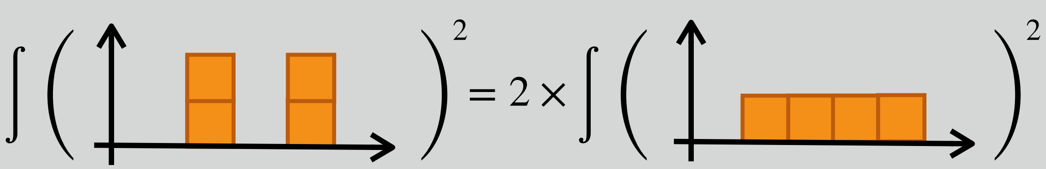
Flux = Particle physics × J : Astrophysical factor $\propto\approx \frac{1}{d^2}\frac{M^2}{V}$



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 (central cusps + substructure **boost**)

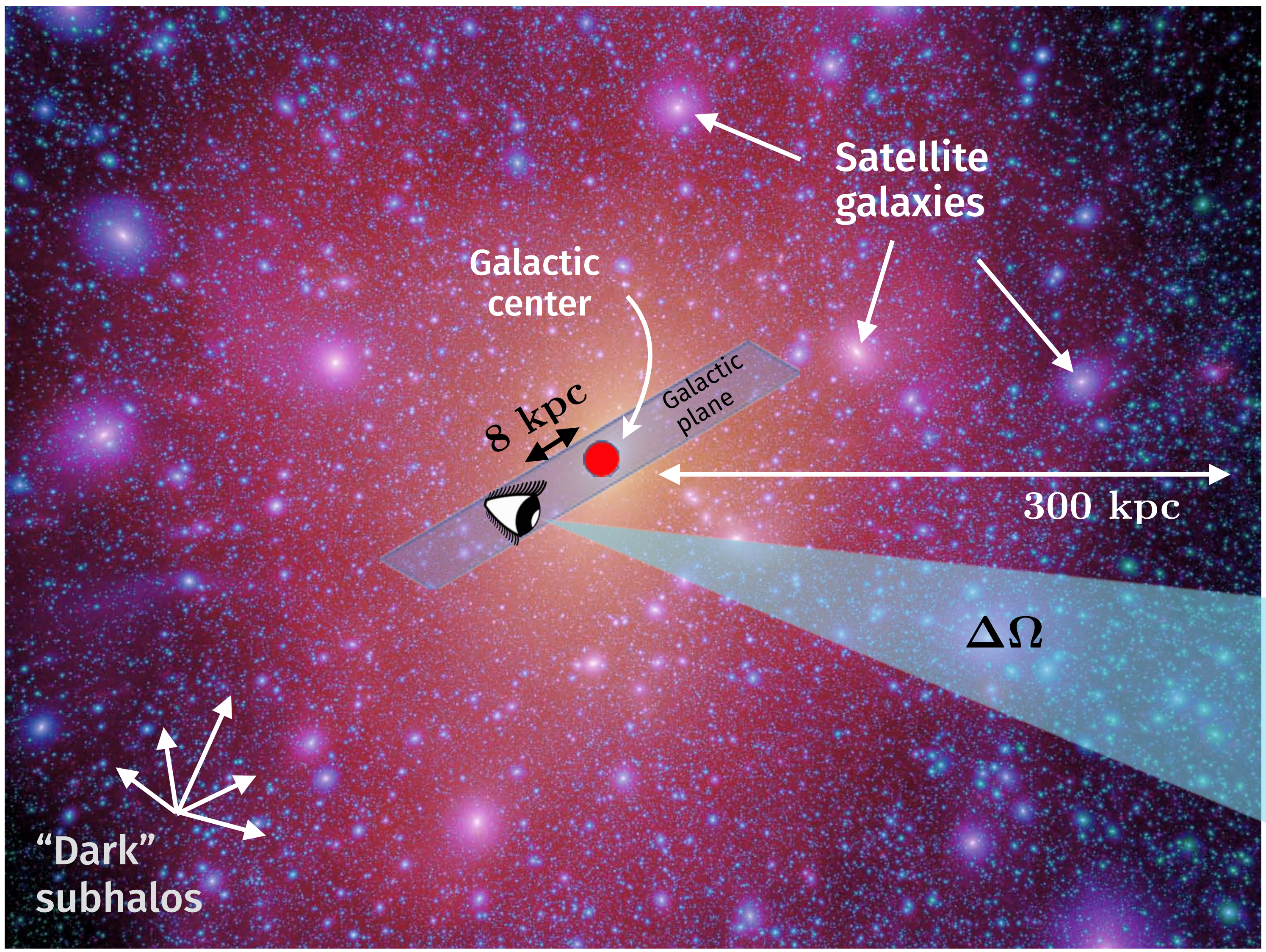


J-factor main uncertainty in indirect DM searches

Indirect DM detection in neutral particles

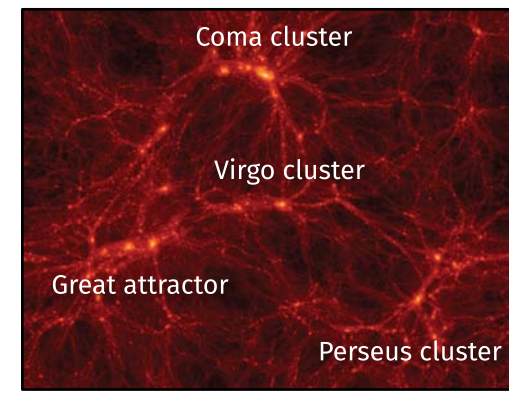
Where to look?

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



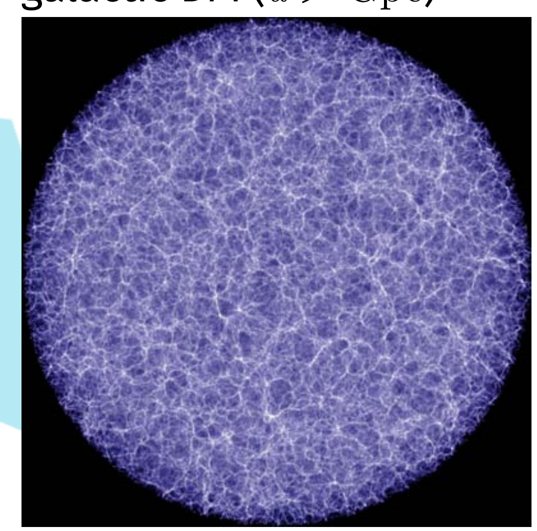
Aquarius simulation – Springel et al. (Nature, 2008)

+ single galaxy clusters ($d >$ Mpc)



Gottlöber et. al. (2010)

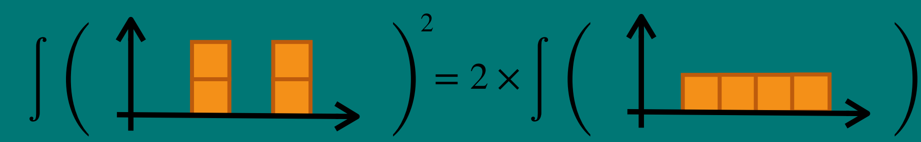
+ ensemble average of extra-galactic DM ($d >$ Gpc)



Angulo et al. (2008)

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

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 $\sim 10-100$

Fraction of halo mass bound in substructure

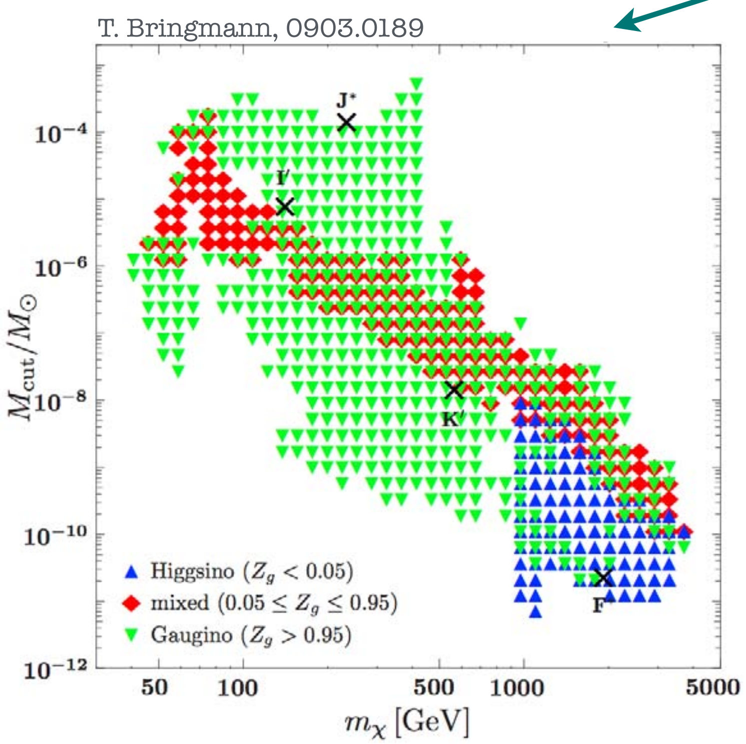
$$\langle J_{\rm sub}\rangle \sim N_{\rm sub}\int_{M_{\rm min}}^{M_{\rm max}} \mathscr{L}(M)\,\frac{{\rm d}P_M}{{\rm d}M}\,{\rm d}M$$

Minimal substructure mass dependent on DM particle mass

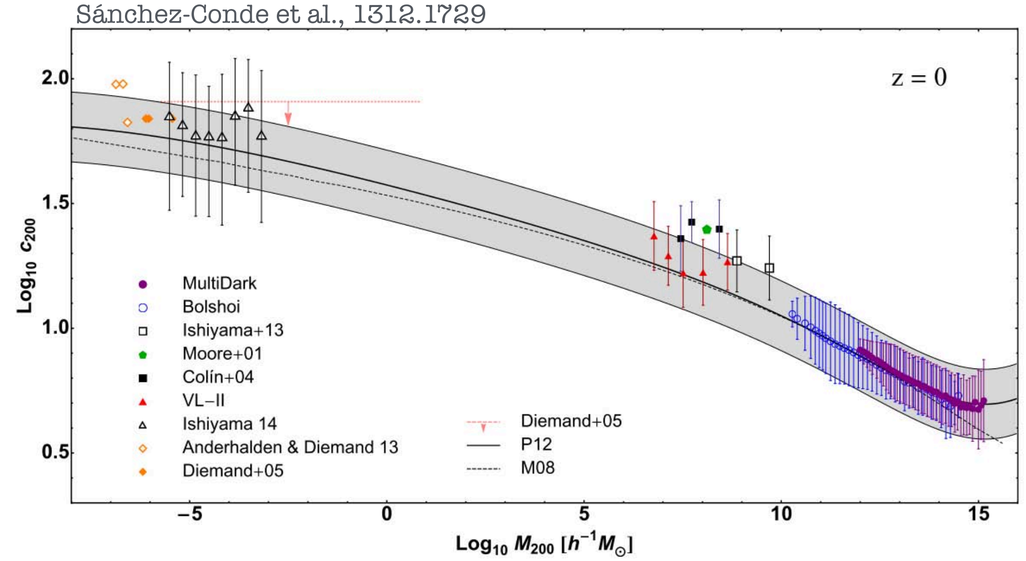
Substructure luminosity sensible to substructure concentration

Large number of small-scale clumps

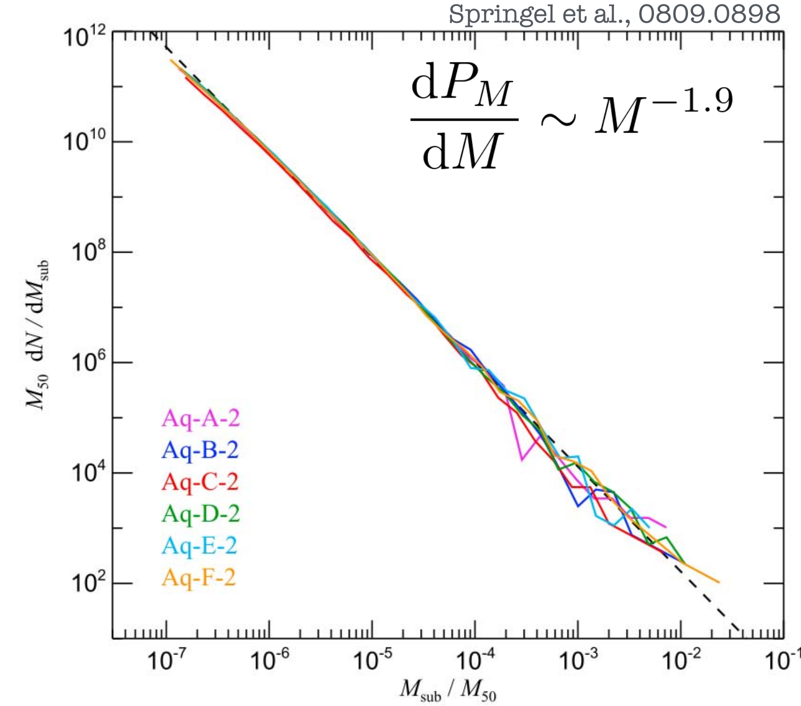
T. Bringmann, 0903.0189



Sánchez-Conde et al., 1312.1729



Springel et al., 0809.0898



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

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(*) Shin'ichiro's talk yesterday

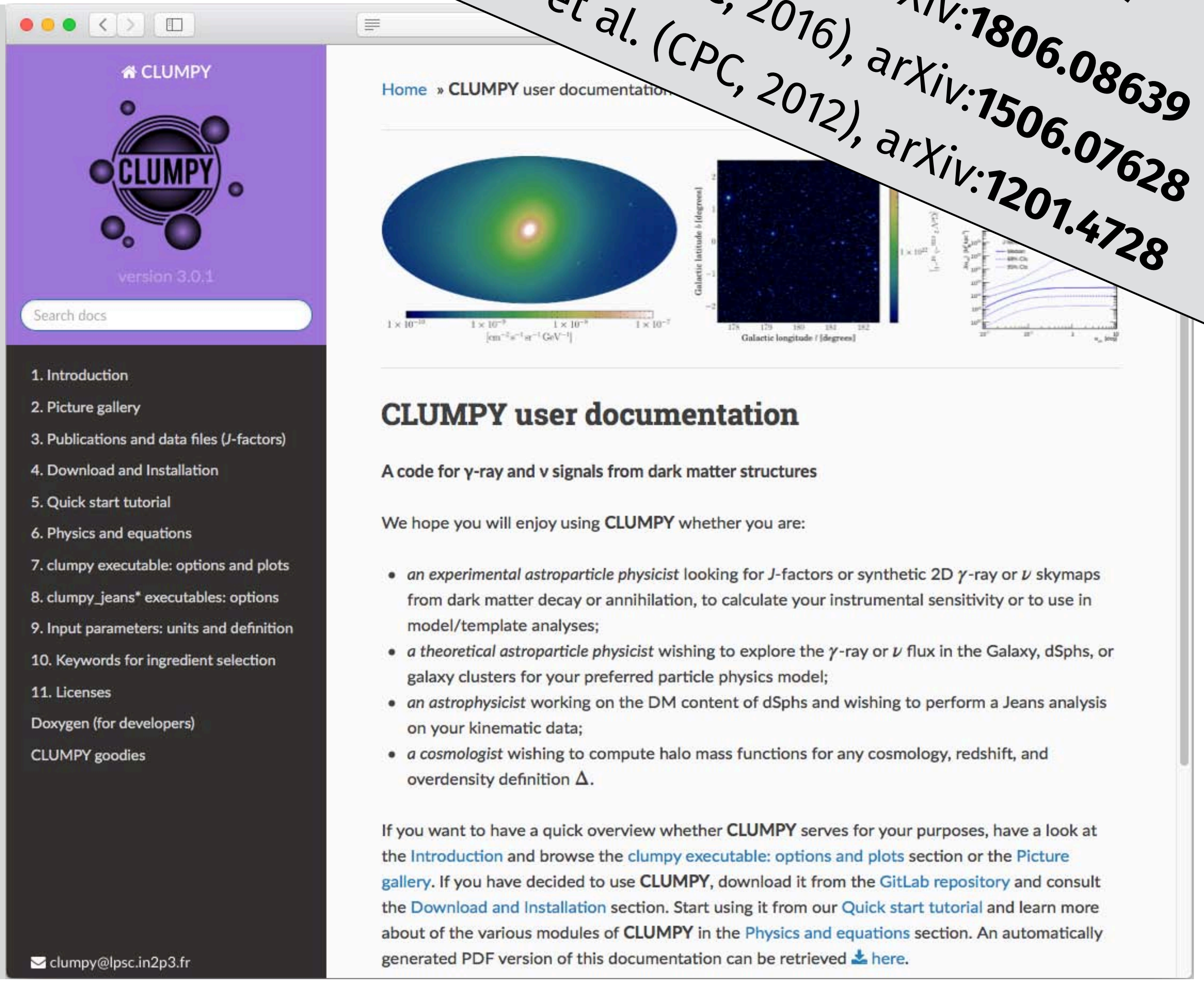
2. The code

```
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

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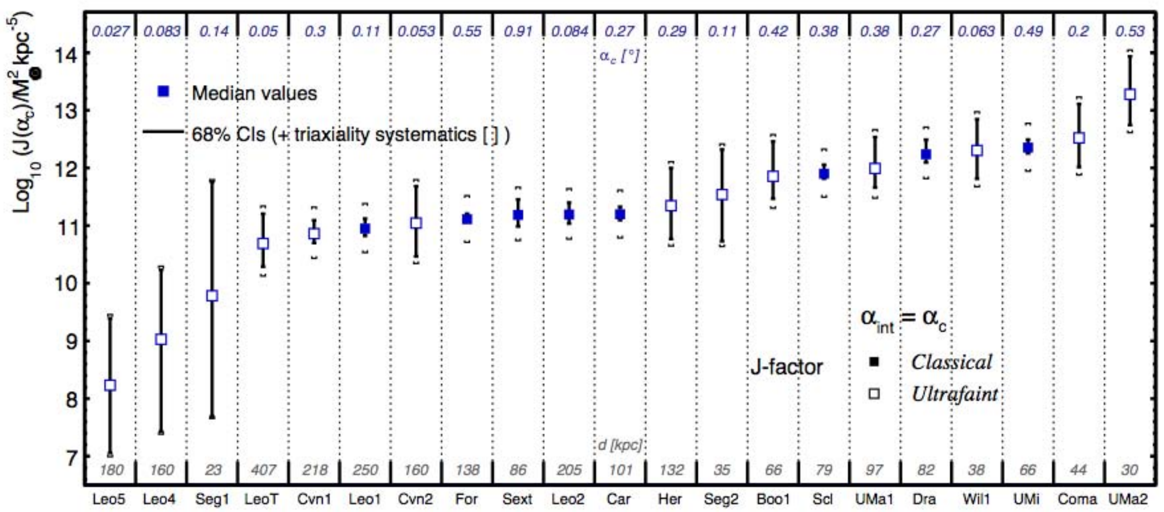
CLUMPY features (I): $\rho_{\rm sm} + \rho_{\rm subs} \rightarrow J$-factor/flux

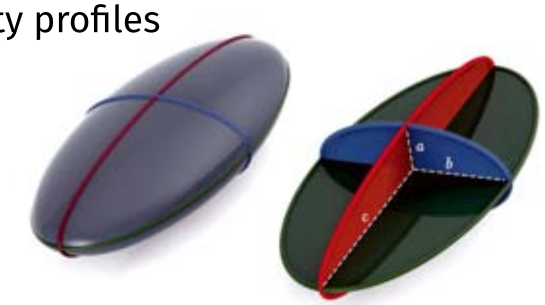
J-factors/fluxes of individual objects (e.g. dSph's) from **pre-defined DM profiles**

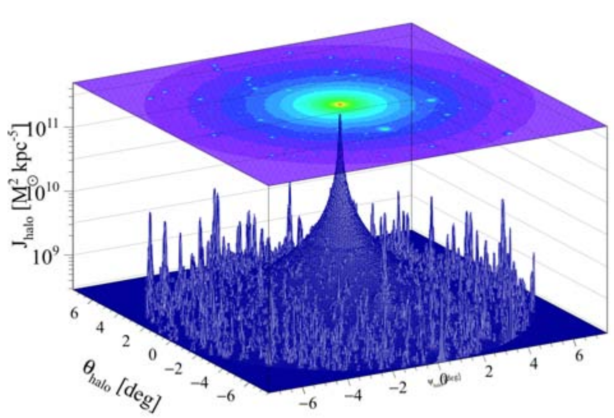
- Propagate **errors from DM profile** to J-factor and DM limit (Bonnivard ApJ, MNRAS, 2015)
- Take into account **substructures**:
  - resolved (statistical) + unresolved: **boost**
  - Multiple levels of self-similar sub-subclustering
- allow **triaxial distortion** of halo profile (semiaxis ratio a, b, c)
- Compute **differential/integral fluxes** (1D and 2D), relying on PPPC4DMID (Cirelli et al., 2010)
- **2D images** with **Gaussian smoothing** + different formats: ROOT, FITS Healpix, FITS image

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

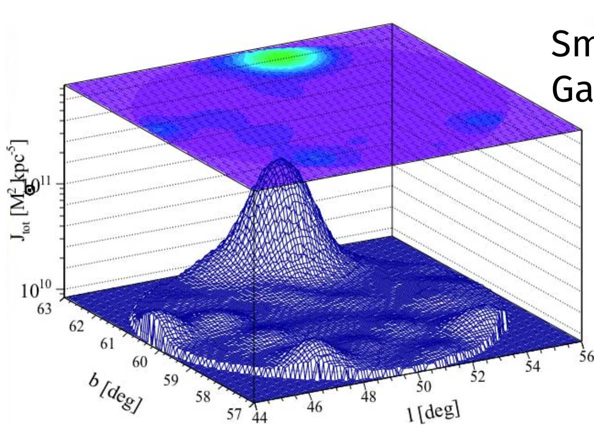


Triaxial DM density profiles

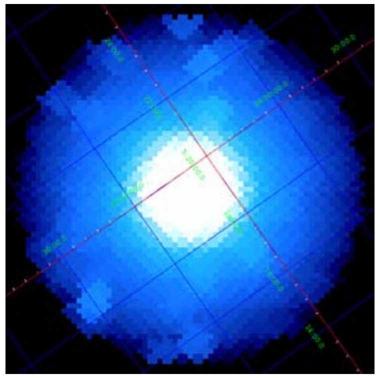




LMC $\mathrm{d}J/\mathrm{d}\Omega$ profile with resolved substructure



Smoothing with Gaussian beam



projected FITS image

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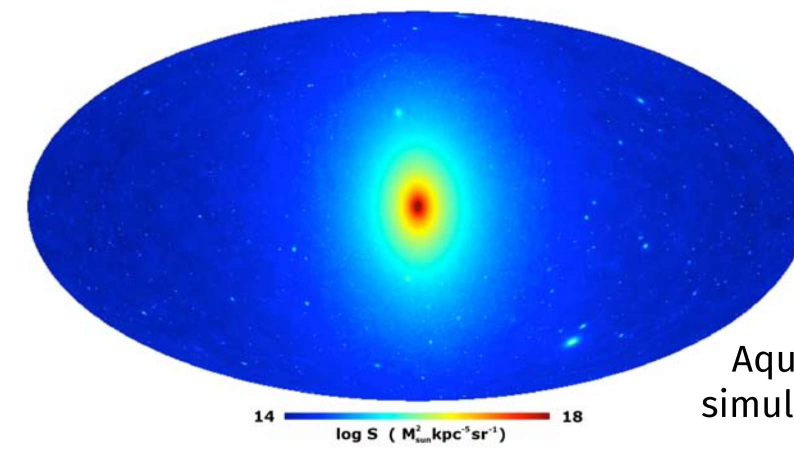
CLUMPY features (II): Full-sky MW analysis with subhalos

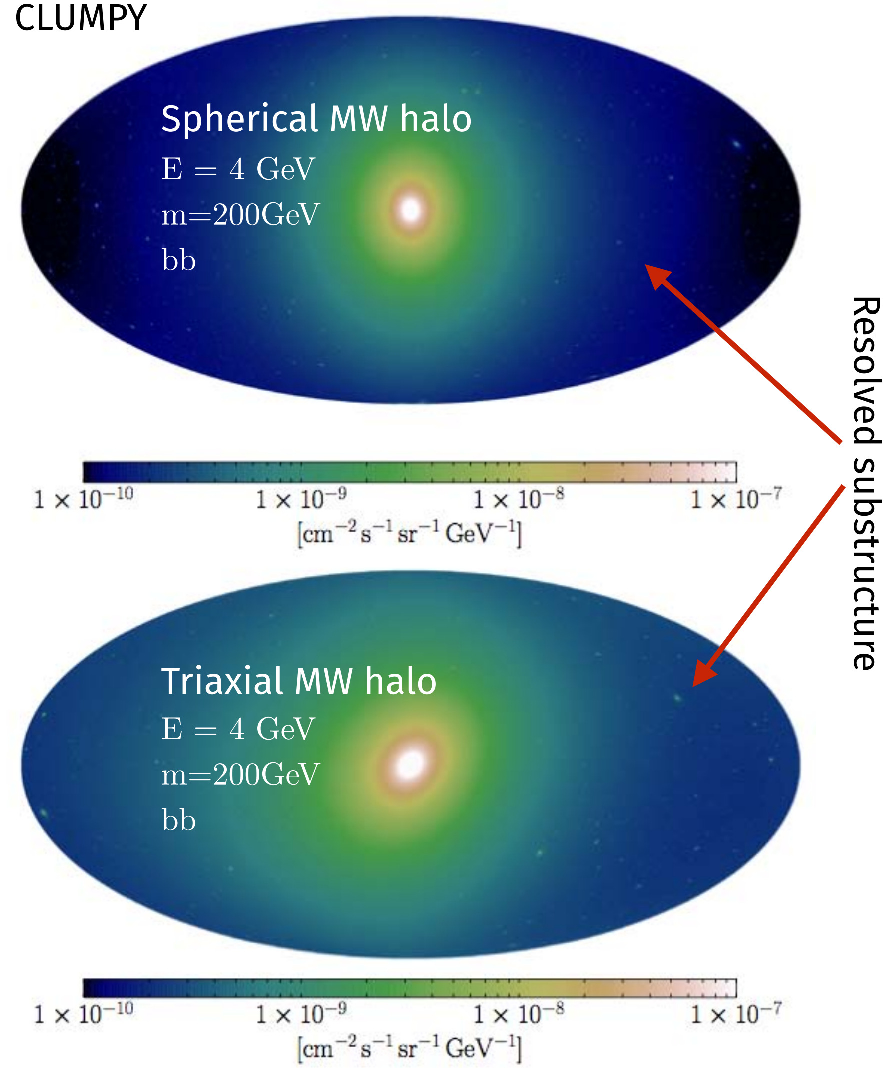
Skymaps of full or partial J-factor sky from DM in the Milky Way halo

- 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,...)



Aquarius simulation

CLUMPY



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

$\sigma_p^2(R)$ ← projection ← $\bar{v}_r^2$

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

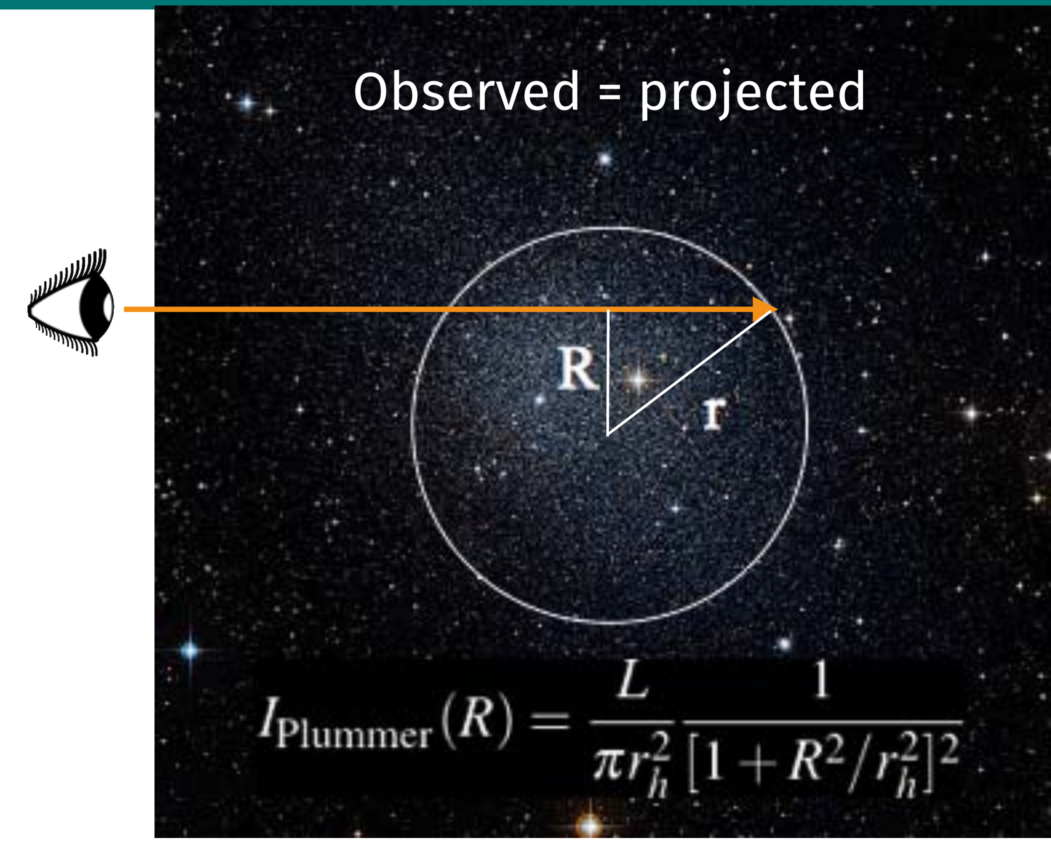
DM model

- Dark matter profile

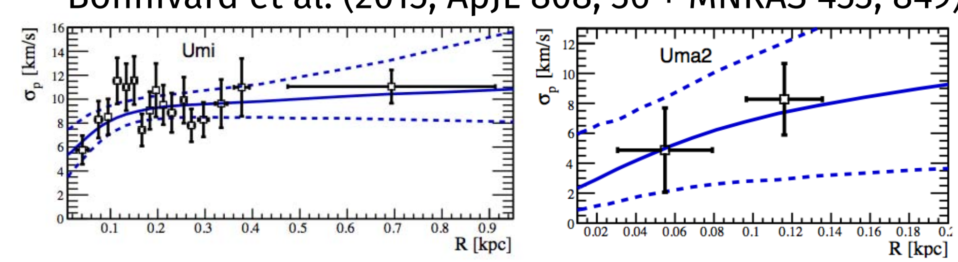
$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1+\left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}}$$

Fit

- χ^2 or MCMC analysis to extract DM parameters ρ_s, r_s, α, β, γ, and $\beta_{\rm ani}$



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

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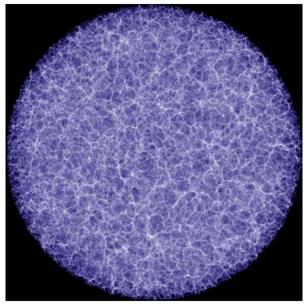
CLUMPY features (IV): Extragalactic diffuse intensity

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



Intensity multiplier

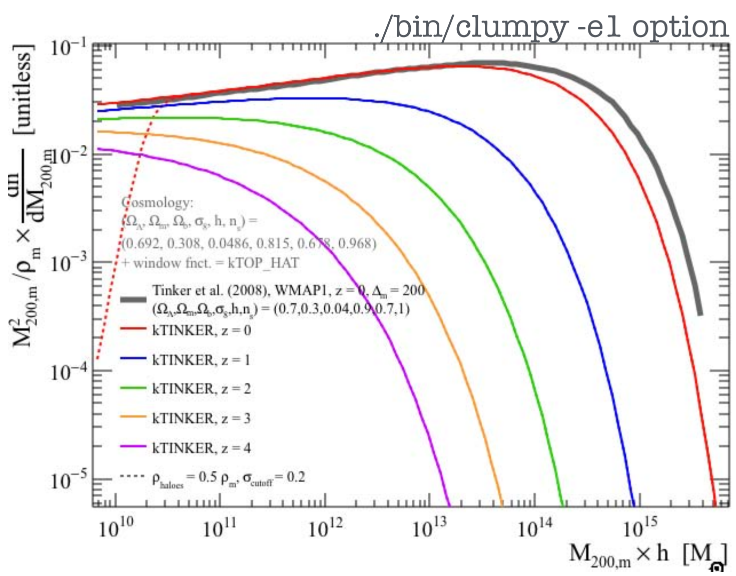
$$\left\langle \delta^2(z) \right\rangle = \frac{1}{\bar{\varrho}^2_{\mathrm{m},0}} \int \mathrm{d}M \frac{\mathrm{d}n}{\mathrm{d}M}(M,z) \times \mathscr{L}(M,z)$$

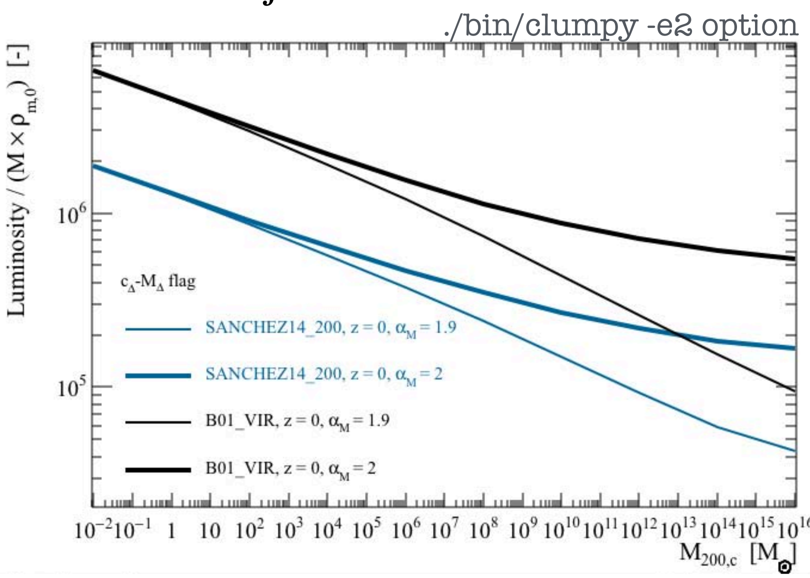
Redshifting of spectrum

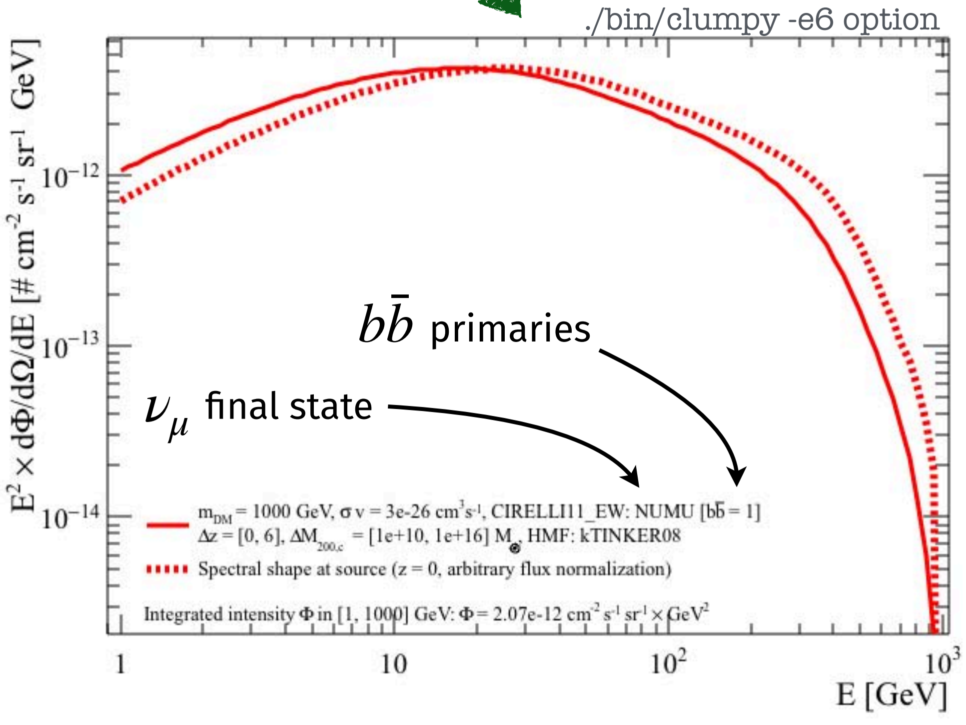
Halo mass function

One-halo luminosities

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

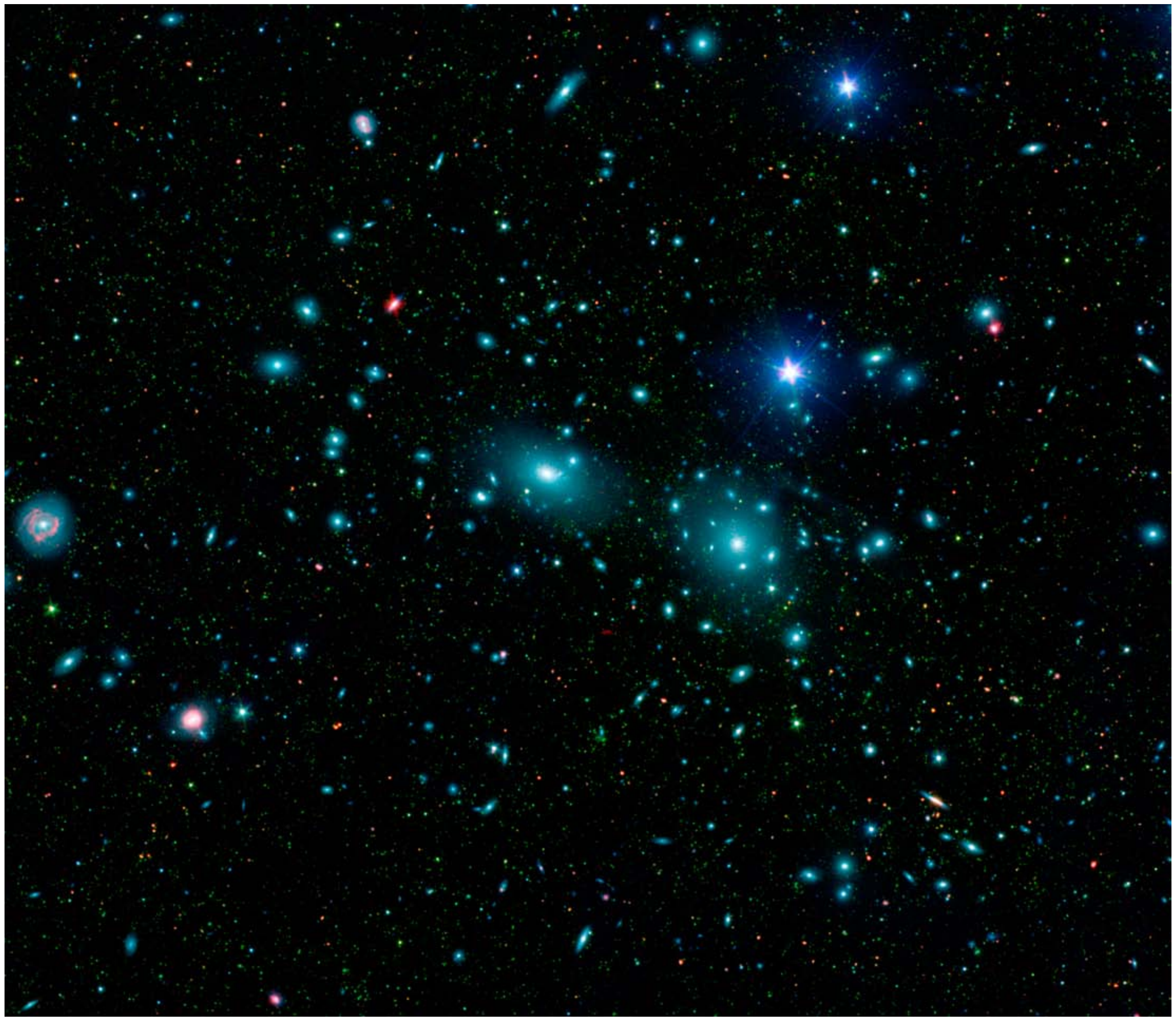






3. On-the-fly code example

Let us calculate the neutrino flux from DM annihilation in the Coma cluster



Total DM halo properties (after 1104.3530):

$z = 0.0234$ (= distance)

$R_\Delta = 2.3$ Mpc

NFW profile with

$r_\mathrm{s} = 609$ kpc

$\rho(r_\mathrm{s}) = 1.61\mathrm{e}5\ \mathrm{M_{sun}/kpc^3}$

(defined in `coma.txt` @ Indico page)

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/**

CLUMPY hands-on

- Make sure to have CLUMPY installed and $CLUMPY environment variable set

```
> $CLUMPY/bin/clumpy
```

Prints help what commands to provide and which modules to select

- Generate a default parameter file to start with

```
> $CLUMPY/bin/clumpy -h2 -D
```

Creates a file `clumpy_params_h2.txt` in the current directory. Rename it to `tutorial.txt`

- Adjust the file, in particular select halo definition given in `coma.txt`
- Compute the J-factors & fluxes as function of the search cone ($\Delta\Omega$ resp. α_{int})

```
> $CLUMPY/bin/clumpy -h2 -i tutorial.txt
```

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CLUMPY hands-on

- Display the energy spectrum for a particular J-factor (search cone)

```
> $CLUMPY/bin/clumpy -z -i tutorial.txt
```

It will complain that some parameters are missing. You have to put the desired J-factor by hand and also again the redshift

- You can also vary a parameter on the command line

```
> $CLUMPY/bin/clumpy -z -i tutorial.txt --gSIM_FLUX_FLAG_NUFLAVOUR=kNUE
```

- Display a 2D image of the object:

```
> $CLUMPY/bin/clumpy -h4 -i tutorial.txt
```

If you switch on smoothing, improve speed with setting `gSIM_HEALPIX_NLMAX_FAC such that lmax <=`

BACKUP: $J_{\rm tot}$ integration, substructures, and boost 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

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

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

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

BACKUP: J_{tot} integration, substructures, and boost factor

- Simple or „smooth“ DM density profile:

  No analytic J-factor expression for usual NFW, Einasto,..
  DM density profiles

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

  - numeric line-of-sight integration needed

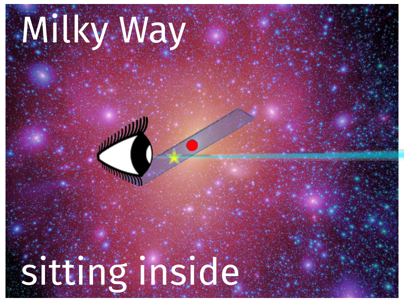
$$\frac{\mathrm{d}J}{\mathrm{d}\Omega} = \int_{l_{\mathrm{min}}}^{l_{\mathrm{max}}} \rho^2 \,\mathrm{d}l$$

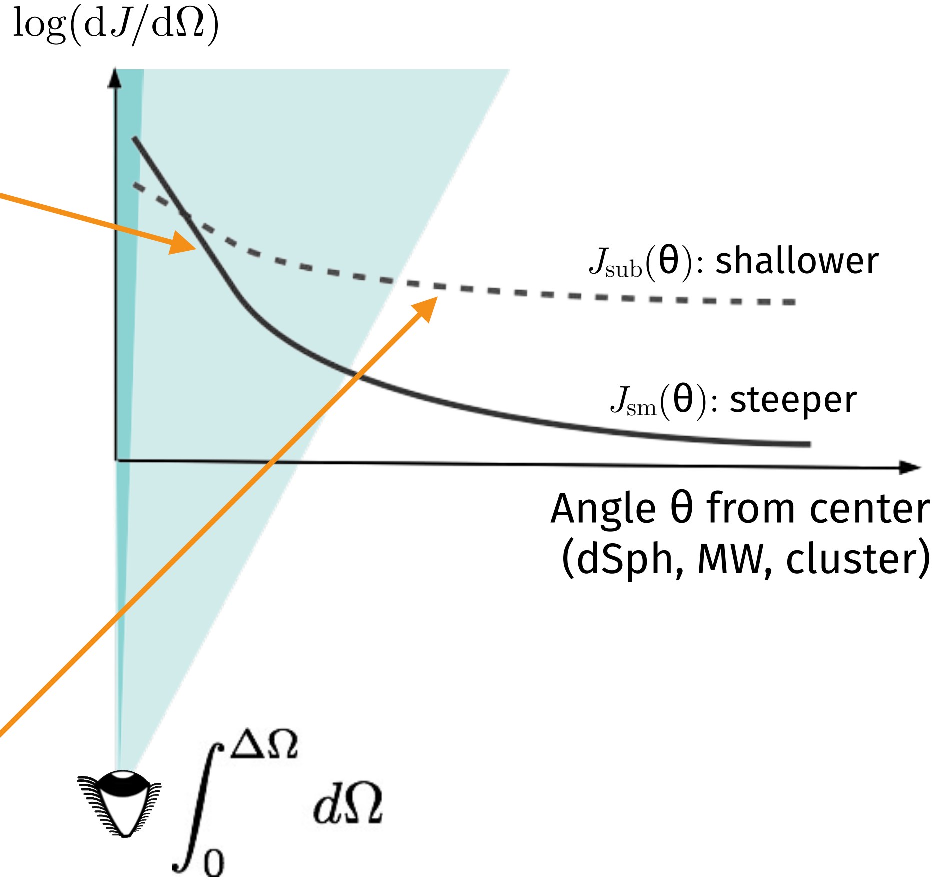
- DM substructure:

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

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

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





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

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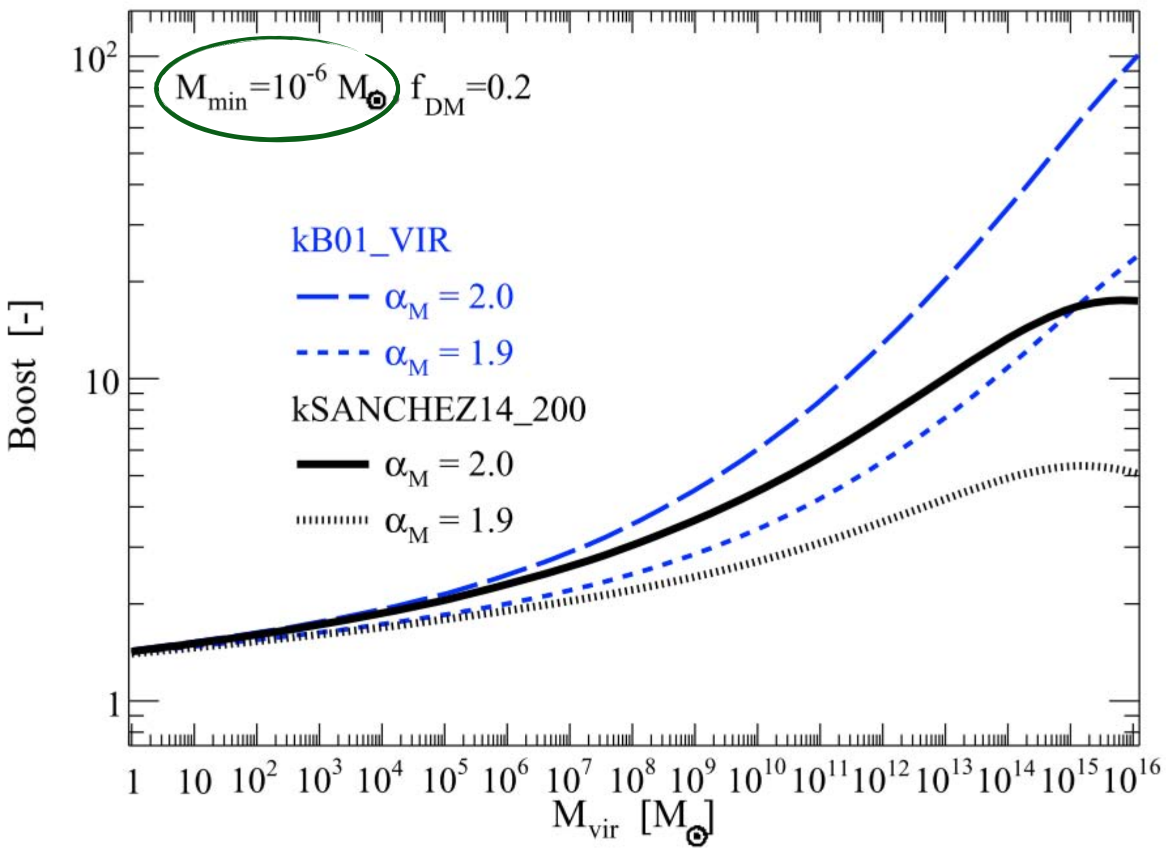
BACKUP: Boost uncertainty (Bonnivard et al., 1506.07628)

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



Also consider self-similar sub-subclustering