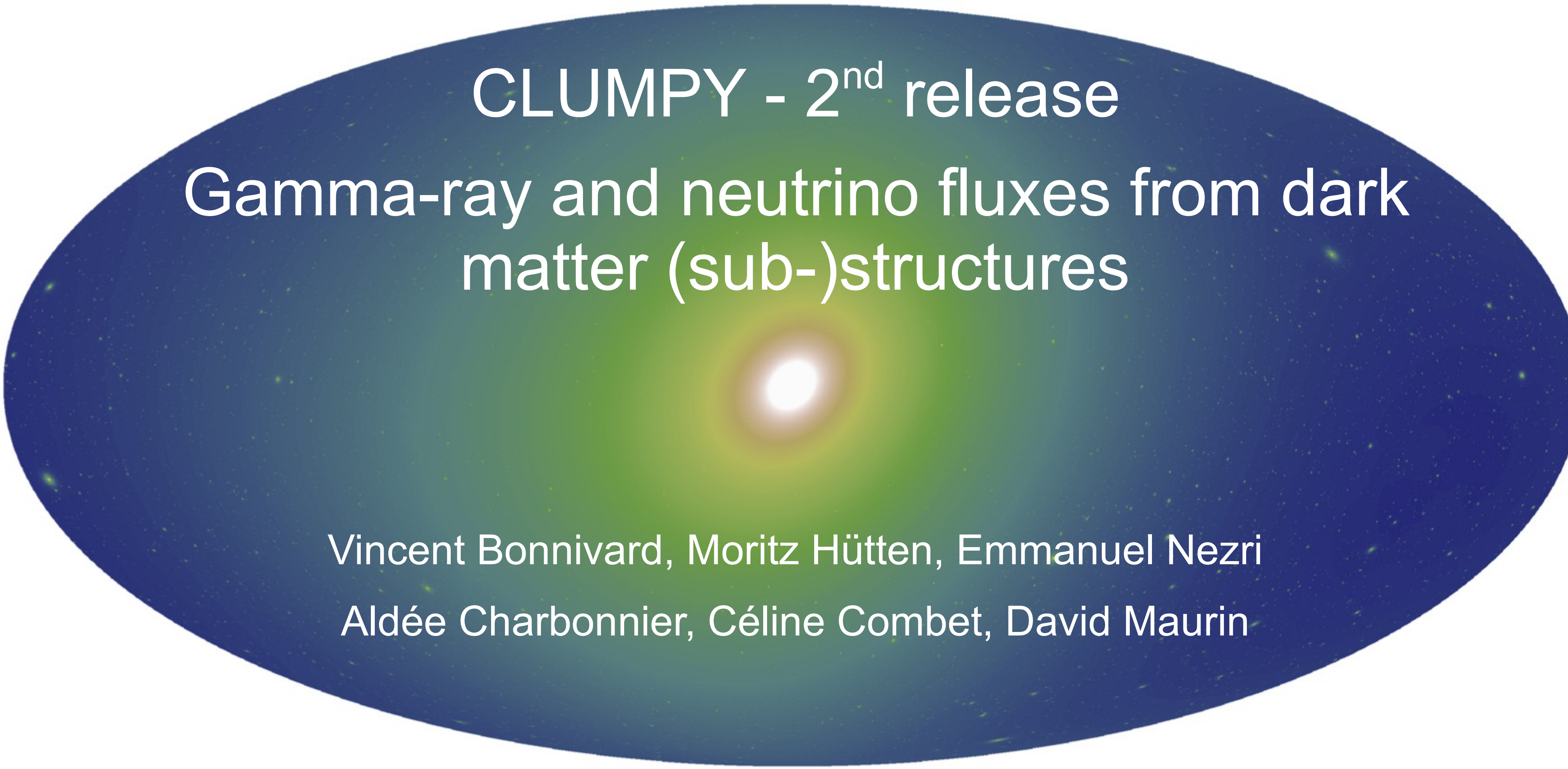


CLUMPY - 2nd release

Gamma-ray and neutrino fluxes from dark matter (sub-)structures

Vincent Bonnivard, Moritz Hütten, Emmanuel Nezri

Aldée Charbonnier, Céline Combet, David Maurin

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

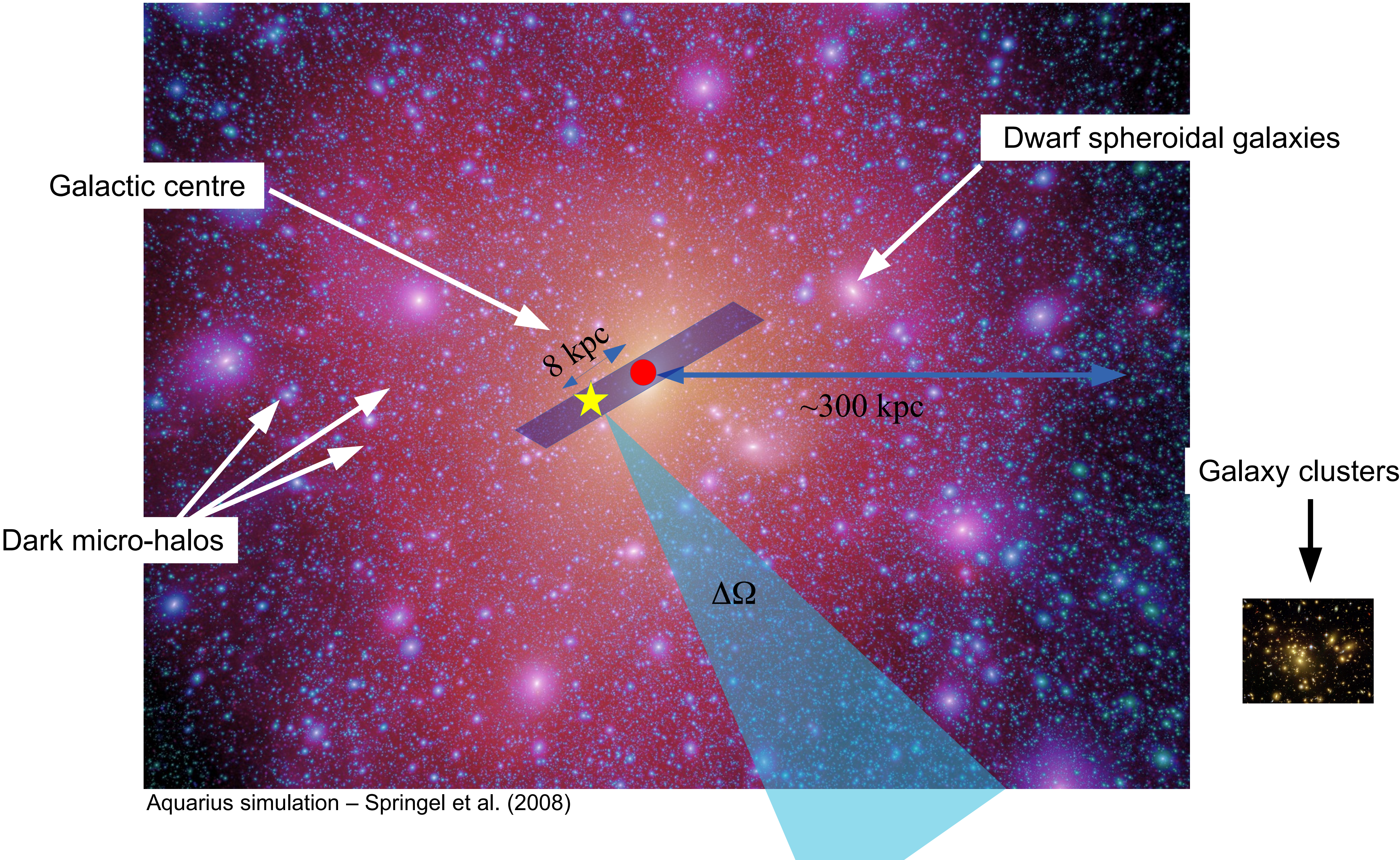
`CLUMPY v2.0`: Bonnivard et al. http://arxiv.org/abs/1506.07628, accepted by CPC
`CLUMPY v1.0`: Charbonnier, Combet, Maurin, CPC 183, 656 (2012)

GdR Terascale, 25/11/2015, Grenoble

Indirect detection in γ-rays and ν

Where to look?

Dense ($\sim \int \rho^2$) – Close ($1/d^2$) – No astrophysical background



Aquarius simulation – Springel et al. (2008)

Indirect detection in γ-rays and ν

The gamma or neutrino flux in given by:

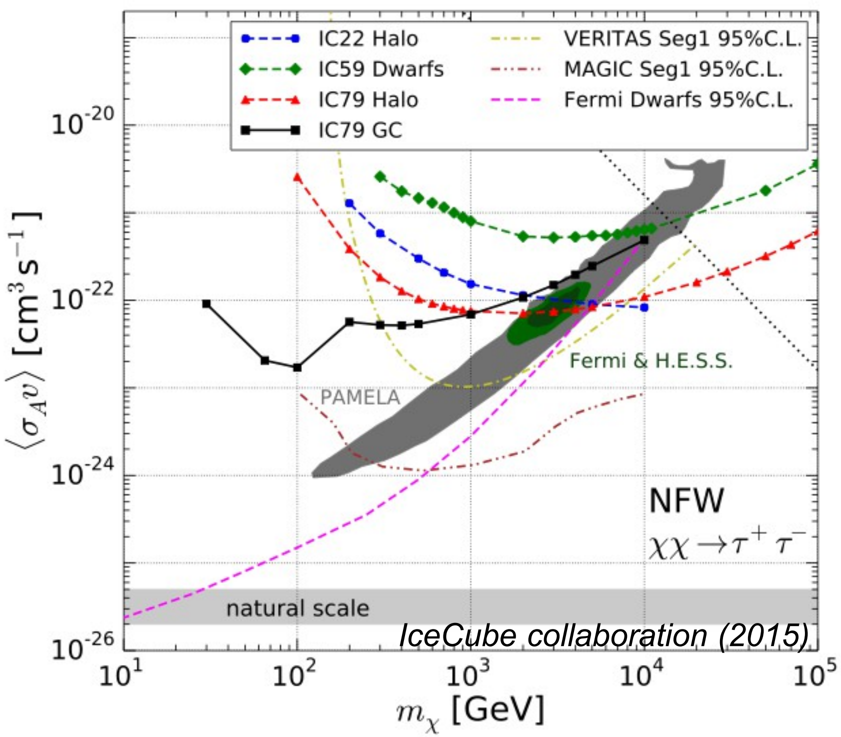
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \psi, \theta, \Delta\Omega) = \frac{d\Phi_\gamma^{PP}}{dE_\gamma}(E_\gamma) \times J(\psi, \theta, \Delta\Omega)$$

Particle physics   Astrophysics

m_{WIMP} ~ 10 GeV – 100 TeV

$$\frac{d\Phi_\gamma^{PP}}{dE_\gamma}(E_\gamma) \equiv \frac{1}{4\pi}\frac{\langle\sigma_{\rm ann} v\rangle}{2m_\chi^2} \cdot \sum_f \frac{dN_\gamma^f}{dE_\gamma} B_f$$

$$J(\psi, \theta, \Delta\Omega) = \int_0^{\Delta\Omega}\int_{\rm l.o.s} \rho^2(l(\psi,\theta))\; dl\, d\Omega$$

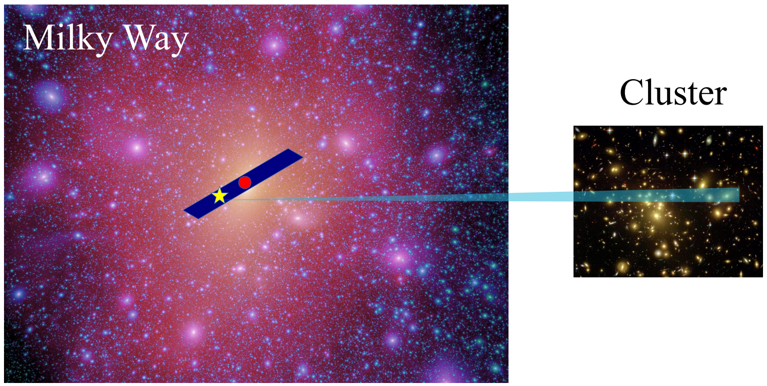


Detection or non-detection

J value and uncertainty must be well-known to put constraints on DM candidate

Signal depends crucially on DM distribution (smooth + substructures)

J_{tot}, substructures, and boost factor

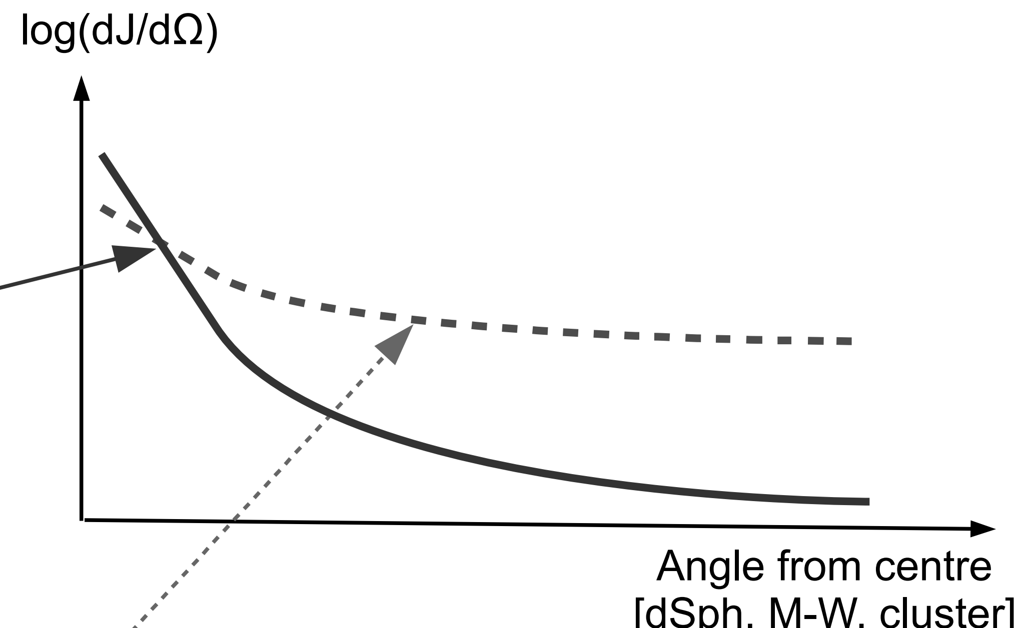


$$J = \int_0^{\Delta\Omega} \int_{l_{min}}^{l_{max}} \frac{1}{l^2} \left(\rho_{sm} + \sum_i \rho_{cl}^i \right)^2 l^2 dl d\Omega$$

Smooth (involves ρ_{sm}^2)

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

→ peaked near centre

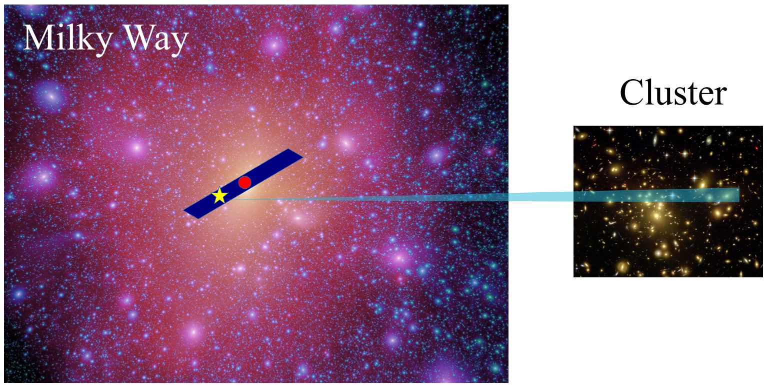


Subs (involves ρ_{sub})
N.B.: spat. dist. flatter than ρ_{sm} (near centre)

$$\langle \frac{dJ_{sub}}{d\Omega}(\theta) \rangle = N_{tot} \int_{l_{min}}^{l_{max}} \frac{d\mathcal{P}_V}{dV} \int_{M_{min}}^{M_{max}} \mathcal{L}(M) \frac{d\mathcal{P}_M}{dM} dM$$

→ less peaked (centre), shallower decrease

J_{tot}, substructures, and boost factor



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

Smooth (involves $\rho_{\rm sm}^2$)

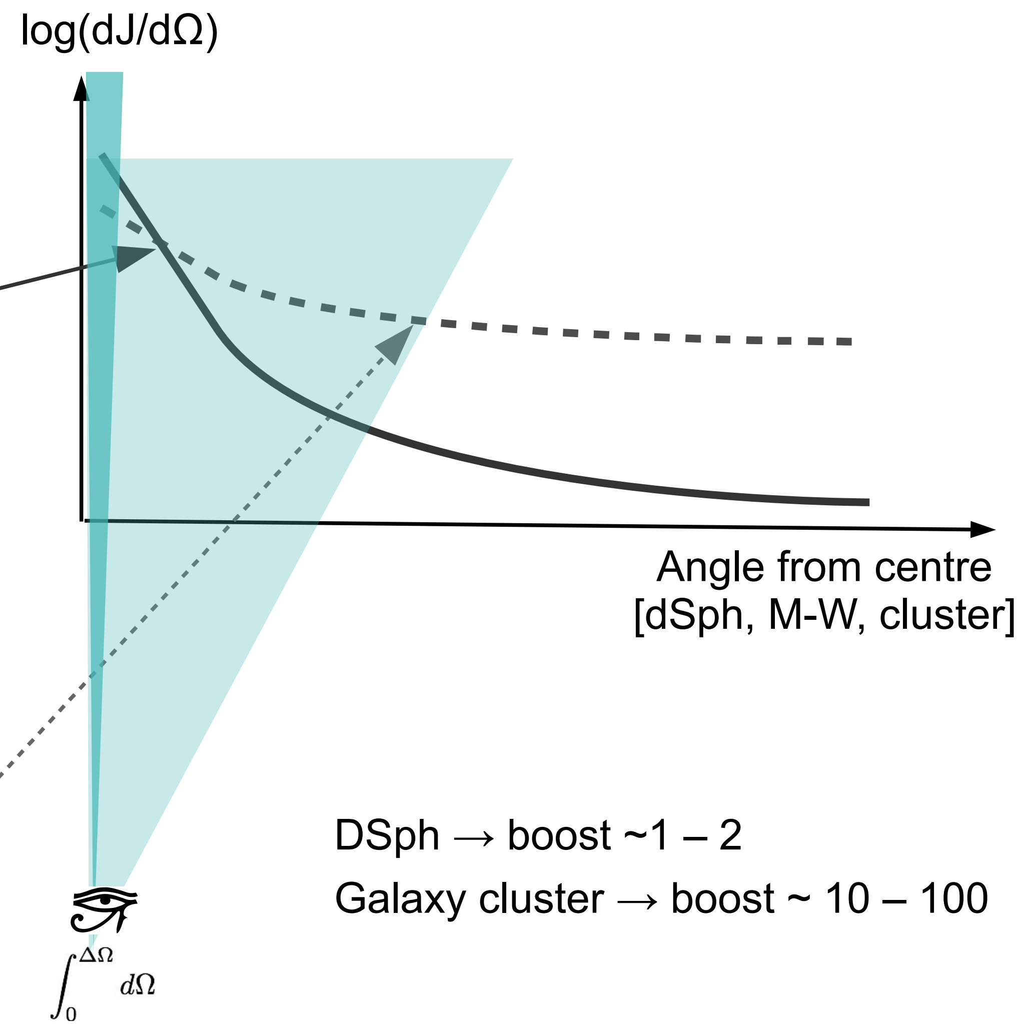
$$\frac{dJ_{\rm sm}}{d\Omega}(\theta) = \int_{l_{\rm min}}^{l_{\rm max}} \rho_{\rm sm}^2 dl$$

→ peaked near centre

Subs (involves $\rho_{\rm sub}$)
N.B.: spat. dist. flatter than $\rho_{\rm sm}$ (near centre)

$$\langle \frac{dJ_{\rm sub}}{d\Omega}(\theta) \rangle = N_{\rm tot} \int_{l_{\rm min}}^{l_{\rm max}} \frac{d\mathcal{P}_{\mathcal{V}}}{dV} \int_{M_{\rm min}}^{M_{\rm max}} \mathcal{L}(M) \frac{d\mathcal{P}_{\mathcal{M}}}{dM} dM$$

→ less peaked (centre), shallower decrease



DSph → boost ~1 – 2

Galaxy cluster → boost ~ 10 – 100

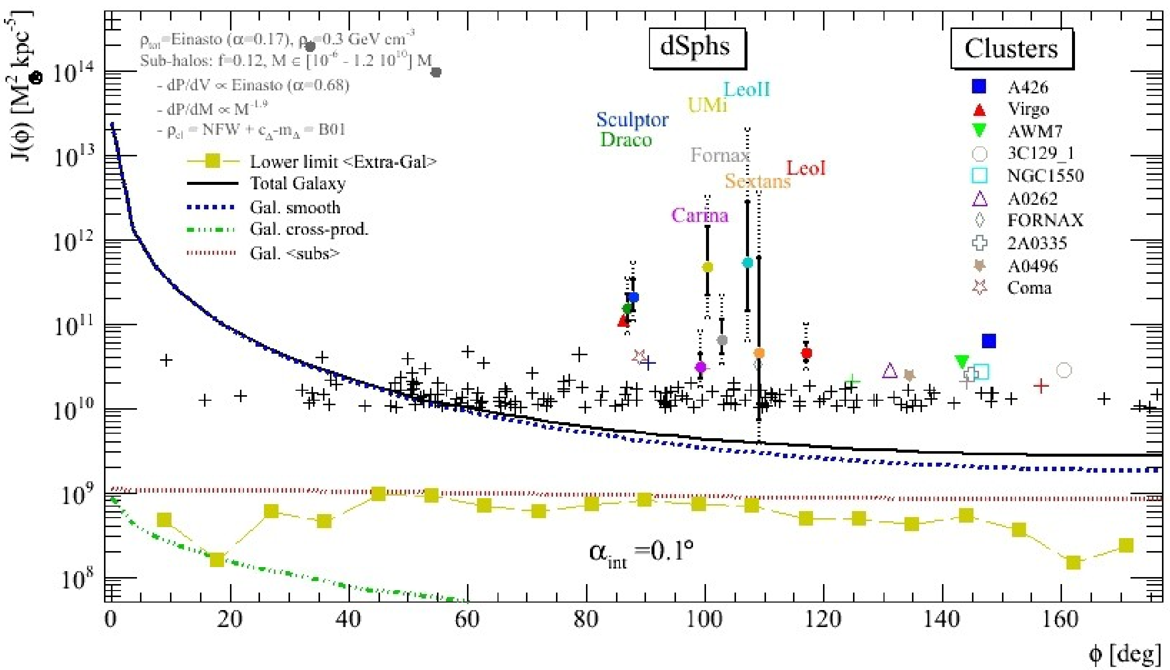
`CLUMPY` – `v1.0` → `v2.0`

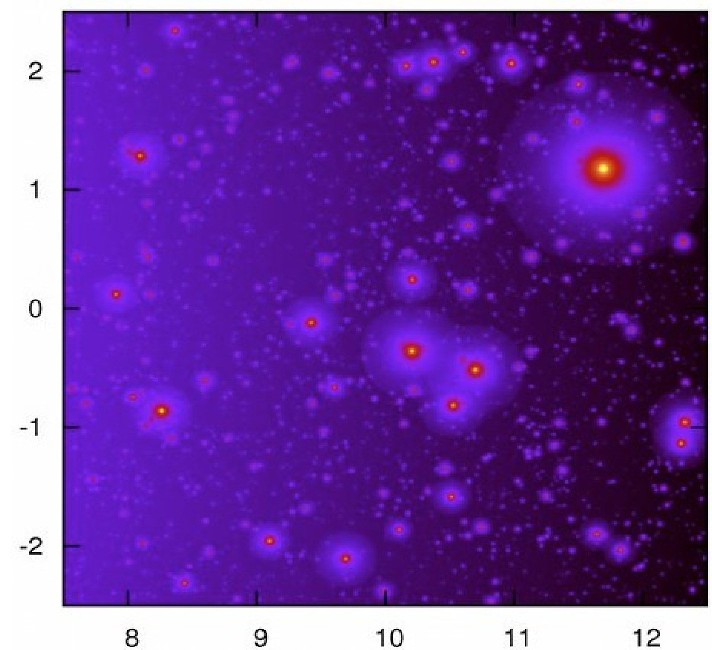
Reconstructing DM profile of dSph – `Jeans` module

CLUMPY v1.0 (2012)

Tool to compute J/D in a variety of configurations, properly taking into account substructures

- J-factors of individual objects (e.g. dSph galaxies) from **pre-defined DM profiles**
- Propagate error bars from DM profiles to J-factors and limits on DM
- Fast J-factors skymaps (simulate N-body simulations end-product)
- C/C++, ROOT, pop-up graphics



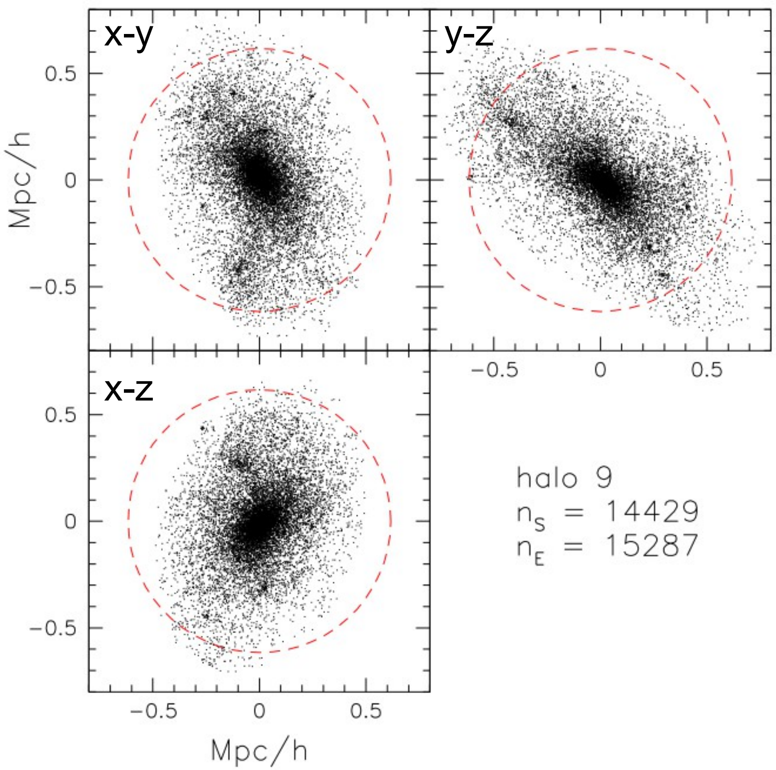


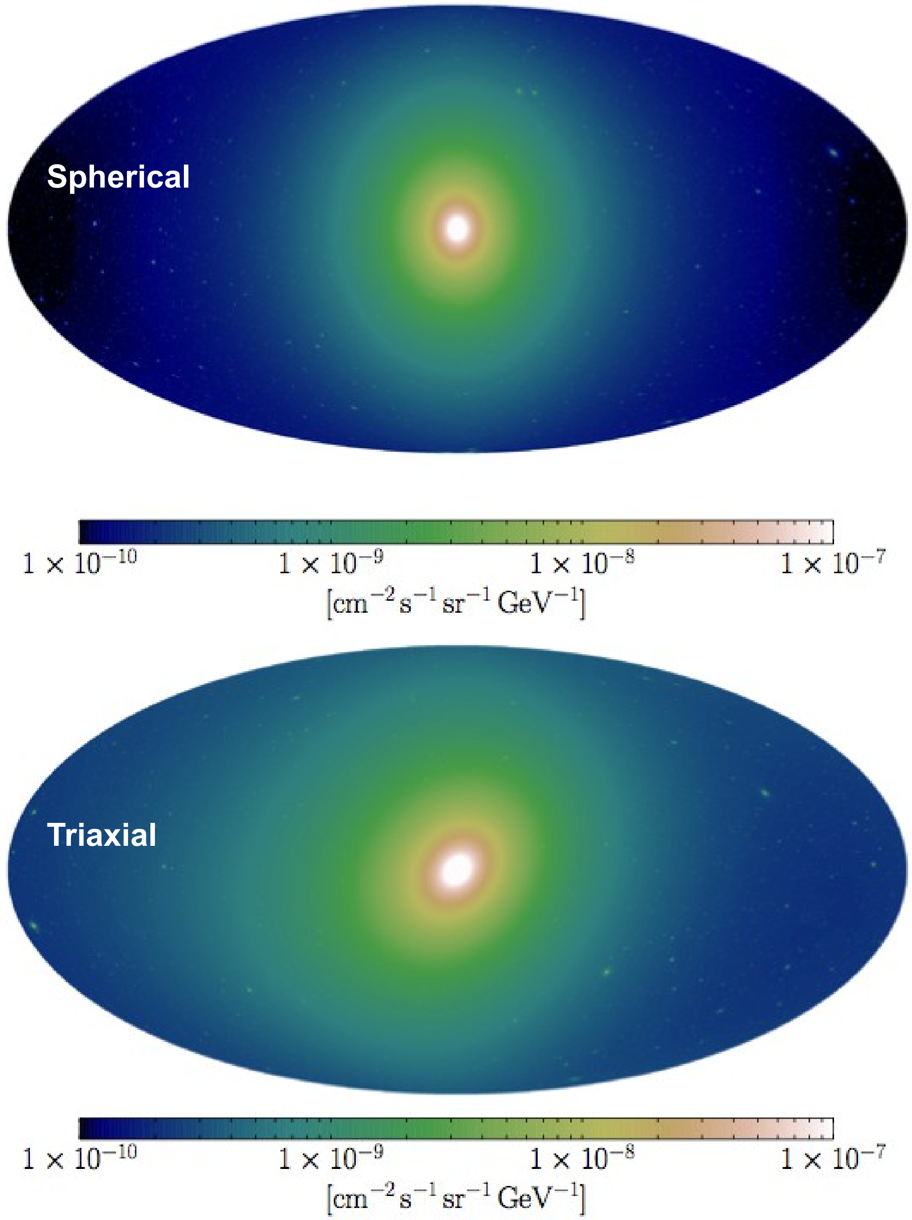
Charbonnier et al. (2011), Nezri et al. (2012), Combet et al. (2012), Maurin et al. (2012)

CLUMPY v2.0 (2015) – new features

- **Triaxiality** – simulations and observations show that DM haloes are triaxial

Despali et al (2013)





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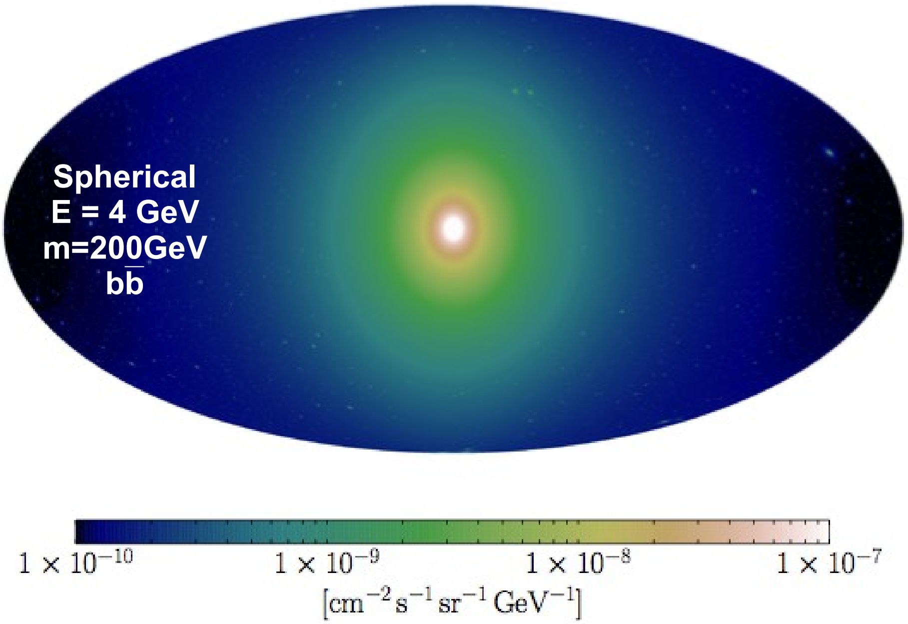
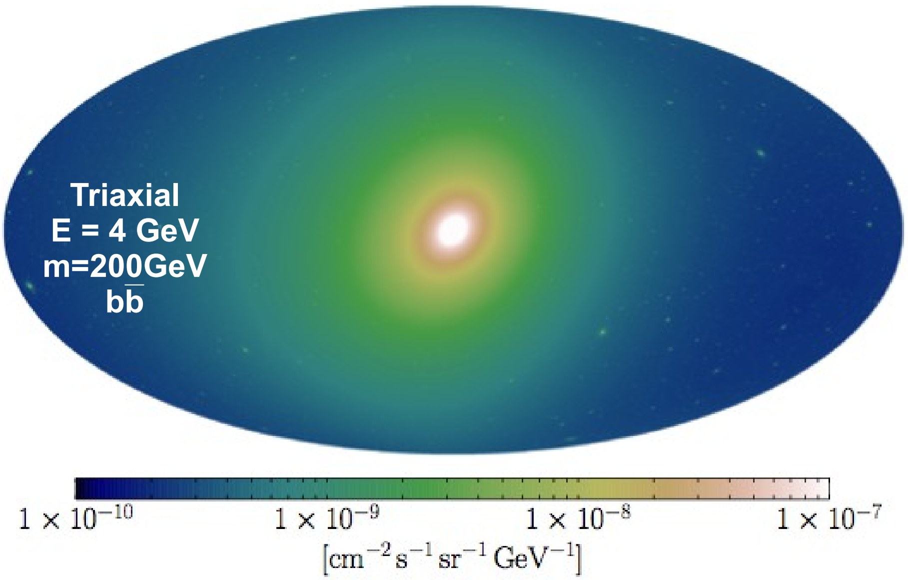
- **Triaxiality** – simulations and observations show that DM haloes are triaxial

- **Gamma and neutrino spectra** computed from PPPC4DMID [Cirelli et al. (2010)]
  → differential flux or integrated flux over given energy range
  → user-defined branching ratios

- **Multi-level boost** (clumps within clumps...)
  → no need to go further than 2 levels





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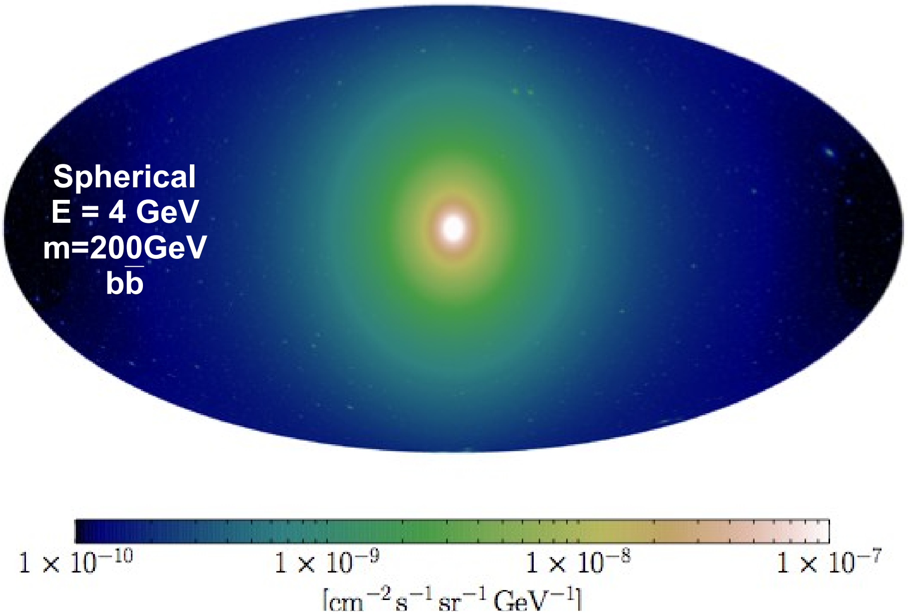
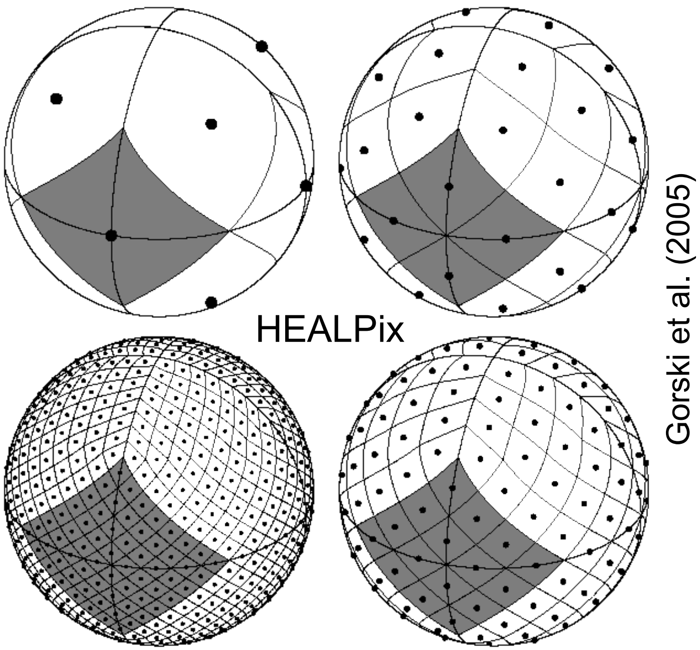
- **Improved outputs:**
  → HEALPix pixelisation scheme for maps
  → ROOT ouputs/pop-up graphics (as v1.0)
  → FITS files (standard astro format)





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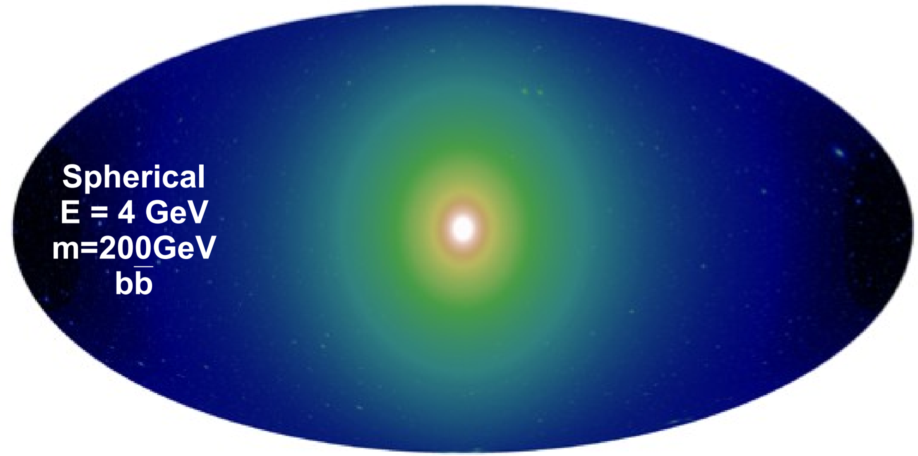
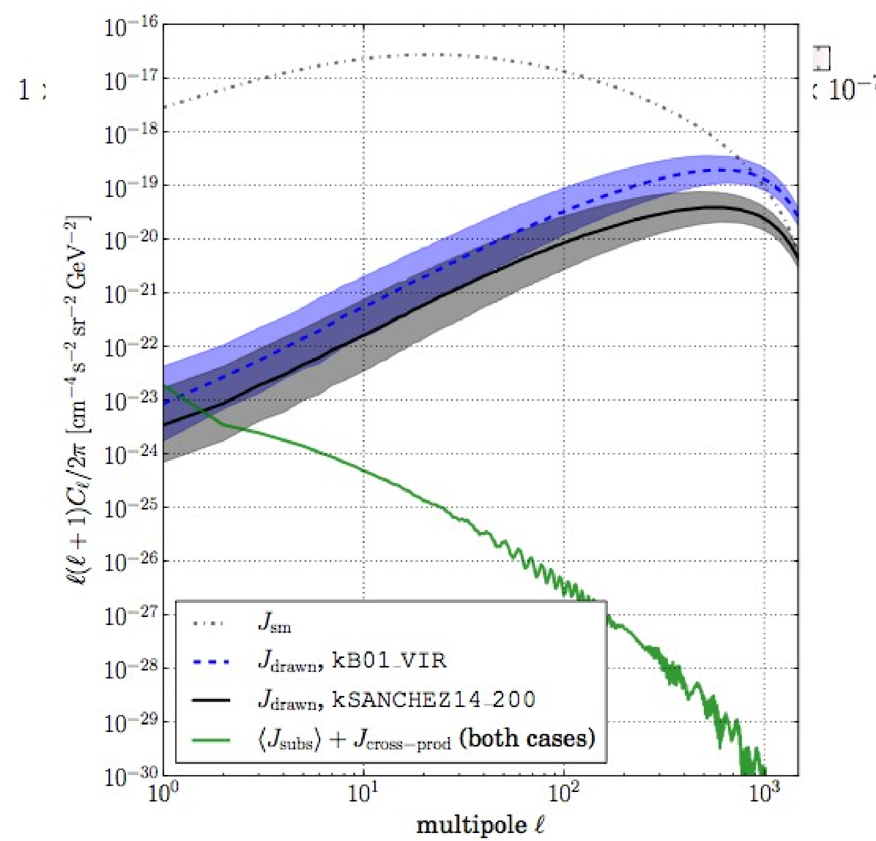
- **Improved outputs:**
  → HEALPix pixelisation scheme for maps
  → ROOT ouputs/pop-up graphics (as v1.0)
  → FITS files (standard astro format)
- **HEALPix-related capabilities**
  → Smoothing by any Gaussian beam
  → Angular power spectrum computation





All controlled from `clumpy_params.txt`

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 [$M_\odot$ 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 × $M_{\rm host}$
gDM_RHOSAT	Saturation density for DM [$M_\odot$ 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)

All controlled from `clumpy_params.txt`

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 τ_{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	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 α_{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_{side} of HEALPix maps (if -1, set to be as close as possible to α_{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)

...and command line interface

CLUMPY Version_2015.06_corr1 https://lpsc.in2p3.fr/clumpy/

Main Page | **Related Pages** | Namespaces | Classes | Files | Search

- CLUMPY
  - Introduction
  - Download / Installation instructions
  - **Quick checks / examples**
  - Contact, bug reports, ASCI files
- Namespaces
- Classes
- Files

Quick checks / examples

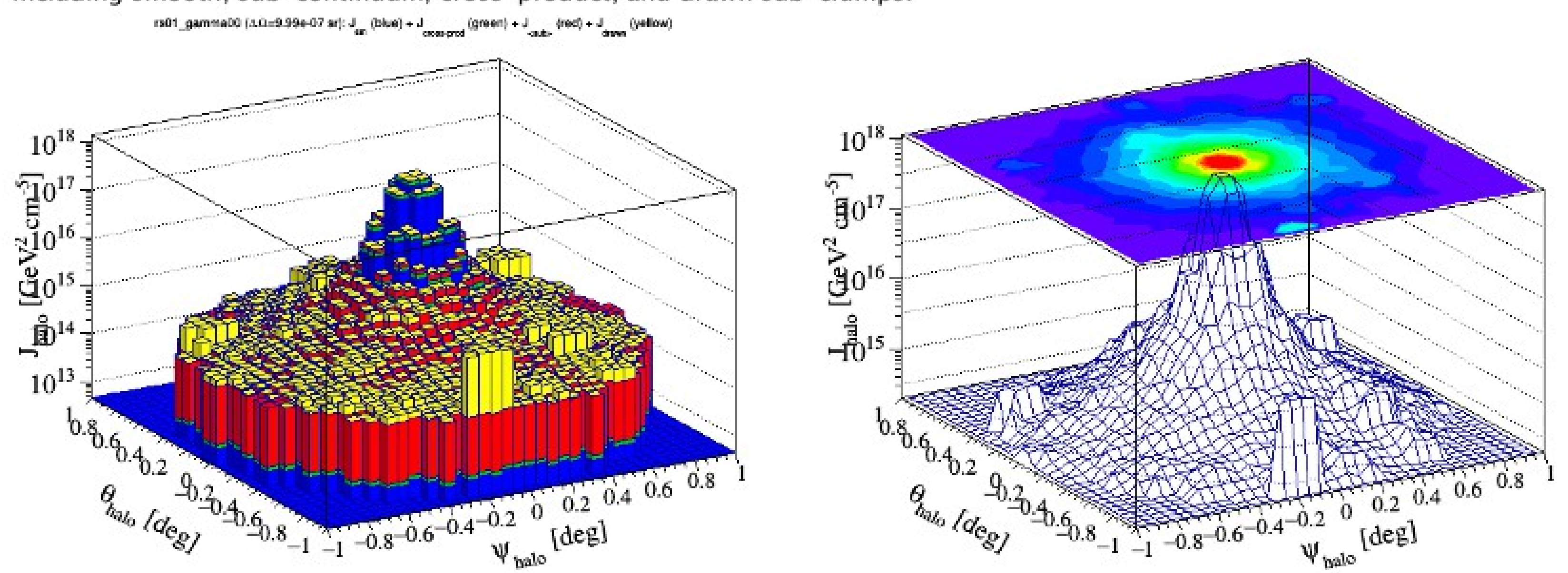
Examples and CLUMPY output

Clumpy commands require an option and a series of arguments. We provide below several examples to illustrate CLUMPY capabilities, but also so that you can check that your CLUMPY installation is successful. The commands are (if you don't use a `bash` shell, drop the 'dot'):

- **J-factors and gamma-ray/neutrino fluxes from DM annihilation**
  - (1) `./bin/clumpy -g` → run for Galactic halo + list of halos [optional]
  - (2) `./bin/clumpy -h` → run on (a list of) non-Galactic halos
  - (3) `./bin/clumpy -s` → run on a file containing a list of likely halo parameters (obtained from a statistical analysis)
  - (4) More extended examples for producing fullsky maps using various masking options:
  - (5) `./bin/clumpy -o` → export FITS file (from 2D maps);
    `./bin/clumpy -f` → append extension with fluxmaps to existing FITS file.
  - (6) `./bin/clumpy -z` → show gamma and neutrino source terms used

- `./bin/clumpy -h5 clumpy_params.txt rs01_gamma00 2. 10.`

  → 2D J-factor including smooth, sub-continuum, cross-product, and drawn sub-clumps.



CLUMPY – v1.0 $\rightarrow$ v2.0

Reconstructing DM profile of dSph – `Jeans` module

From stellar kinematics to DM profile

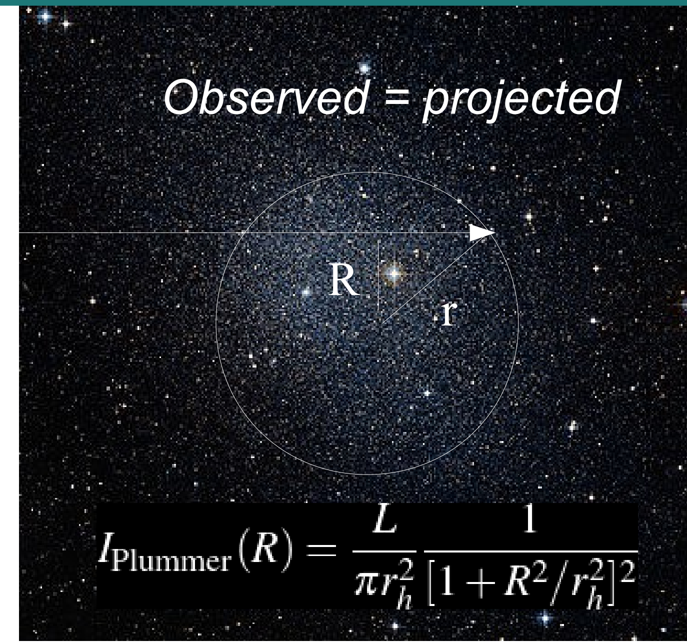
DATA

- **Light profile and velocity dispersion**

$I(R)$ $\sigma_p^2(R)$

Deprojection - Projection

ν $\overline{v_r^2}$



- **Jeans equation: solve for $\overline{v_r^2}$**

MODEL

Stellar density *Radial velocity dispersion*

$$\frac{1}{\nu}\frac{d}{dr}(\nu \overline{v_r^2}) + 2\frac{\beta_{\rm ani}\overline{v_r^2}}{r} = -\frac{GM(r)}{r^2}$$

Collisionless Boltzman
Spherical symmetry

Anisotropy *Enclosed mass*

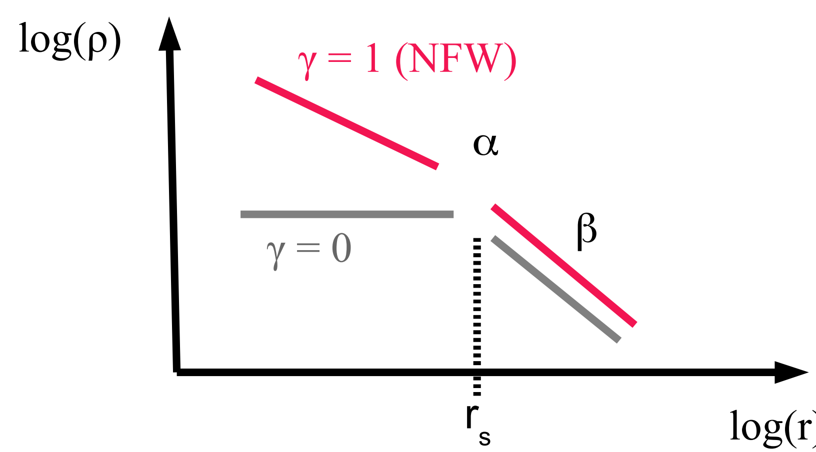
$\beta_{\rm ani} = 1 - \overline{v_\theta^2}/\overline{v_r^2}$ $M(r) = \int_0^r 4\pi s^2 \rho(s) ds$

- **Dark matter profile**

FREE PAR.

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

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

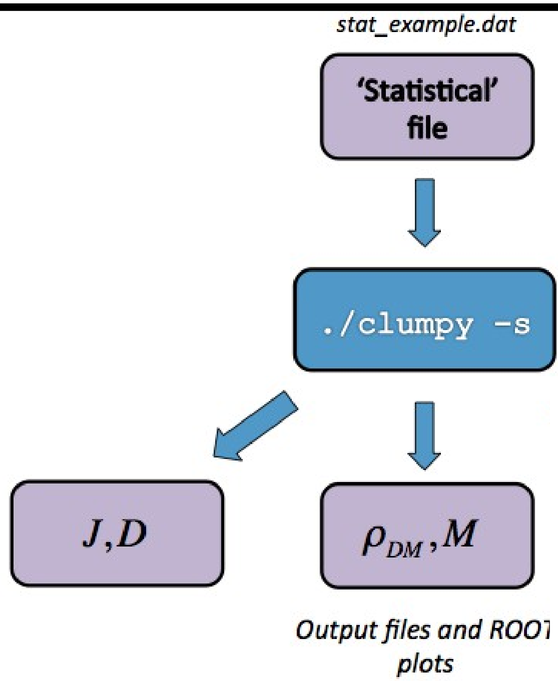


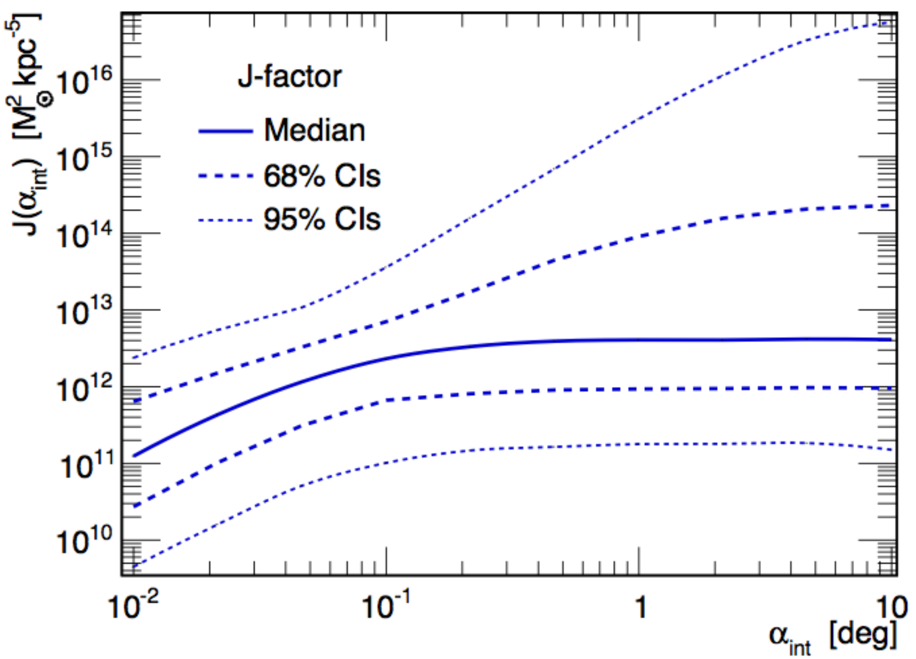
Dsph galaxy analysis

CLUMPY v1.0

Someone else recovers DM profile from dSph kinematic data (Jeans analysis, Chi2 or MCMC)

→ Best fit profile or chains of DM profile parameters





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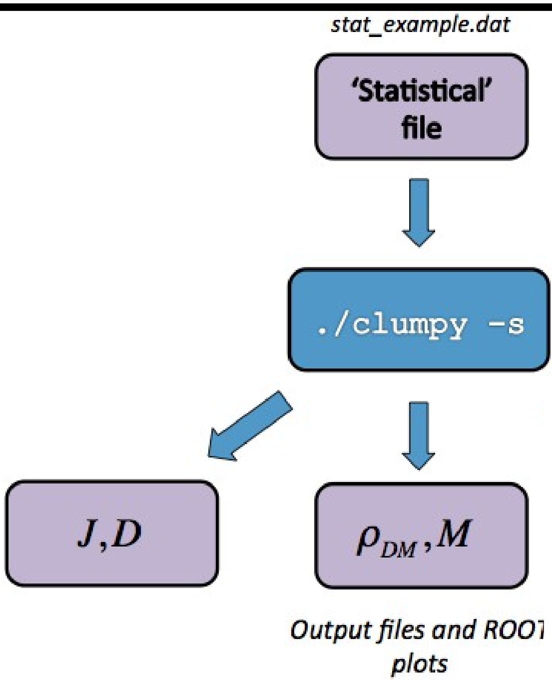
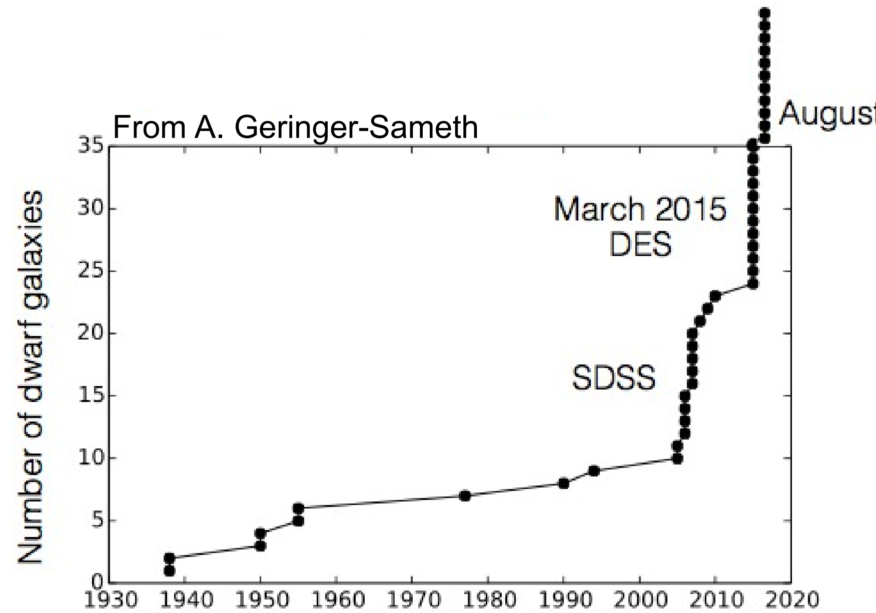




New instruments → a lot more MW's satellite galaxies discovered

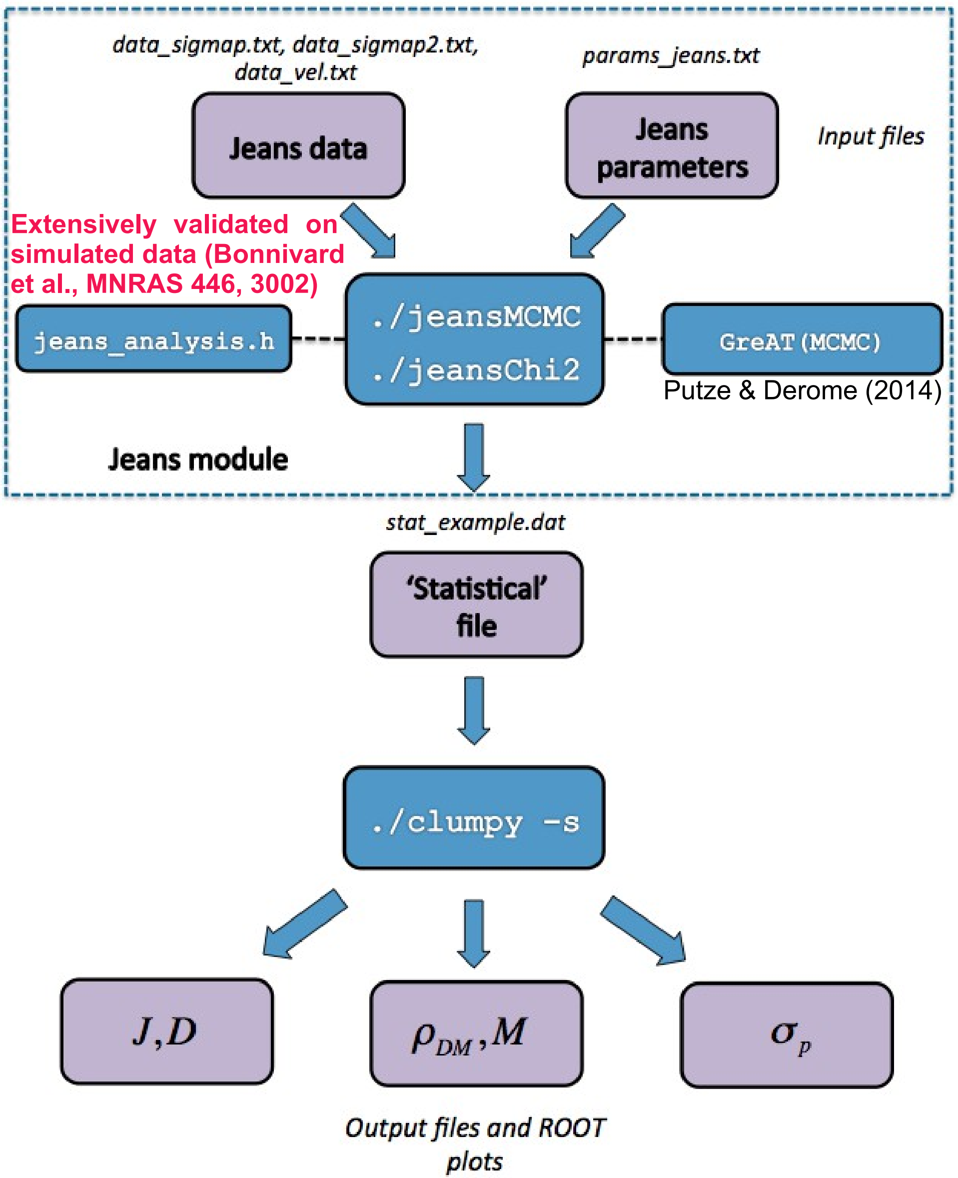
[Some of them, like Ret2, close to us and very interesting for DM indirect detection]

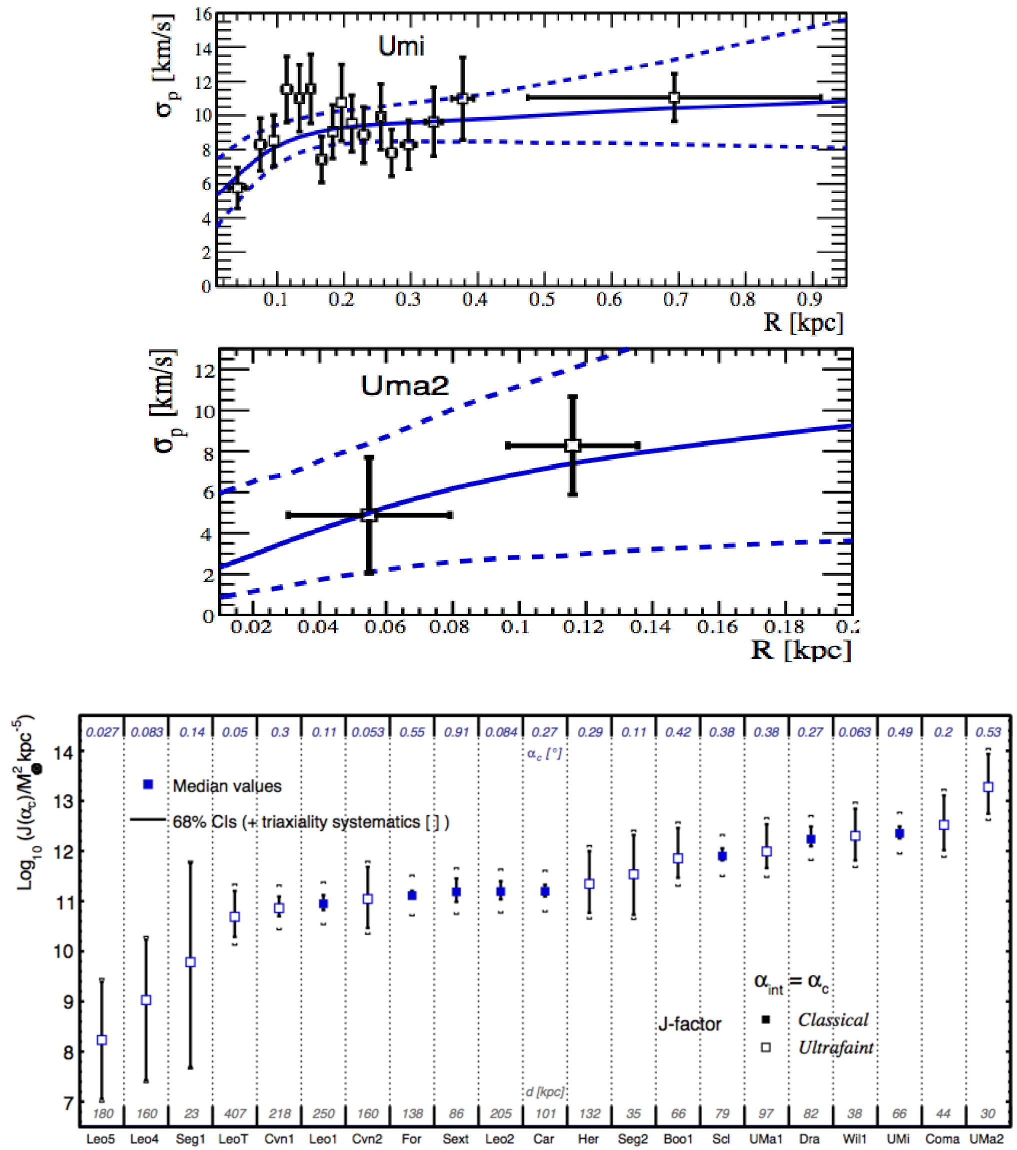
→ extend CLUMPY to reconstruct DM profile from dSph kinematic data in:

- **a fast and efficient way**
- **a more flexibe way**
- **a more controlled way**

Dsph galaxy analysis

CLUMPY v2.0





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

Conclusions

CLUMPY v2.0 is available! https://lpsc.in2p3.fr/clumpy/index.html

- **User-friendly**, fully documented using Doxygen, lots of examples and tests to run

- **Fast computation** of

  - Annihilation or decays **astrophysical factors** using any DM profile

  - **Accurate boost** from substructures

  - Integrated or differential **fluxes in gamma-rays and neutrinos**, using user-defined branching ratios

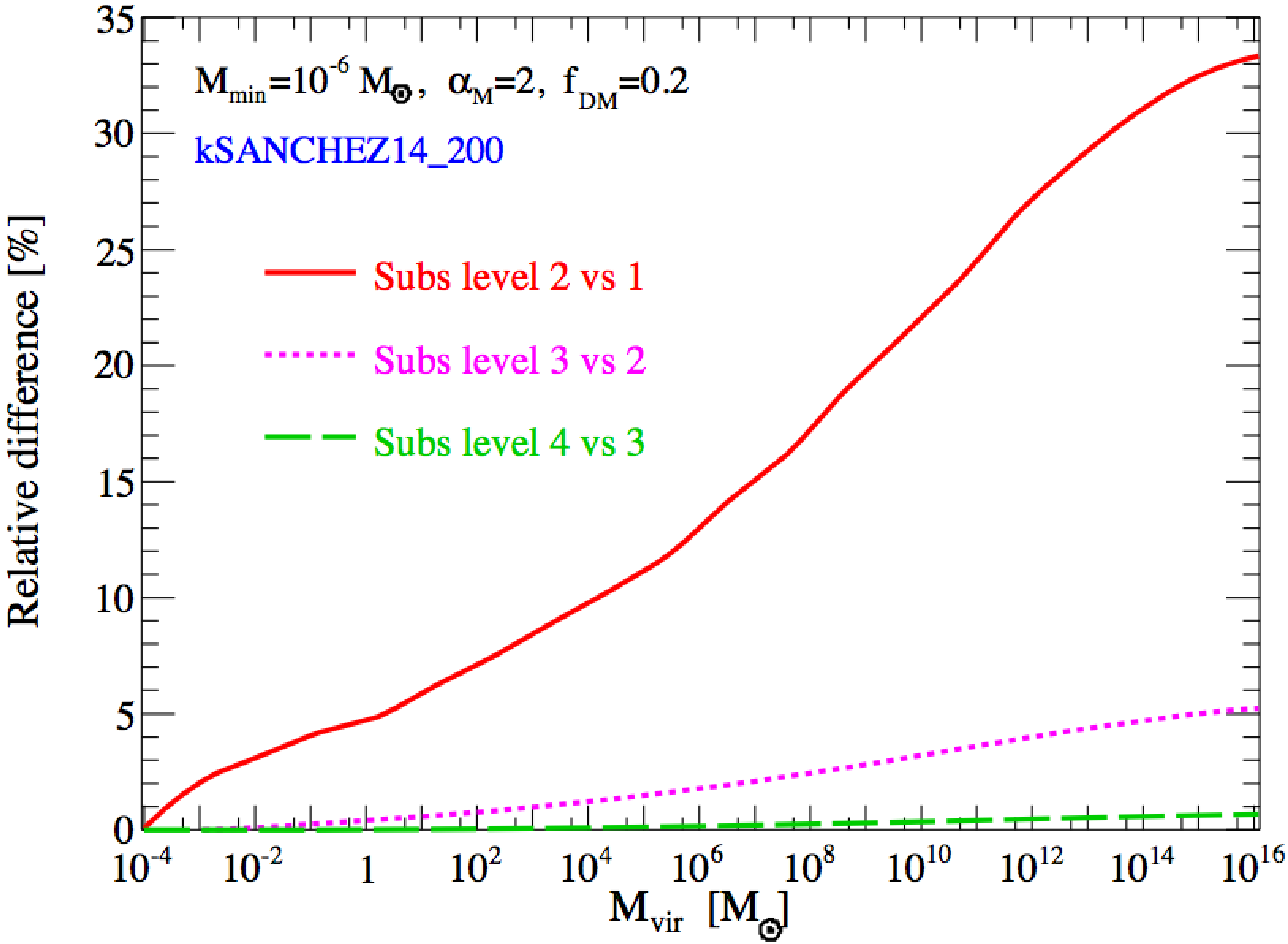
- 2 modes of operation

  → **List of objects** (dSph galaxies, galaxy clusters)

  → **Skymap mode** – fast generation of partial or fullsky maps, with clumps drawn to comply with user-defined mass and spatial distributions. [Triaxiality, HEALPix, power spectrum]

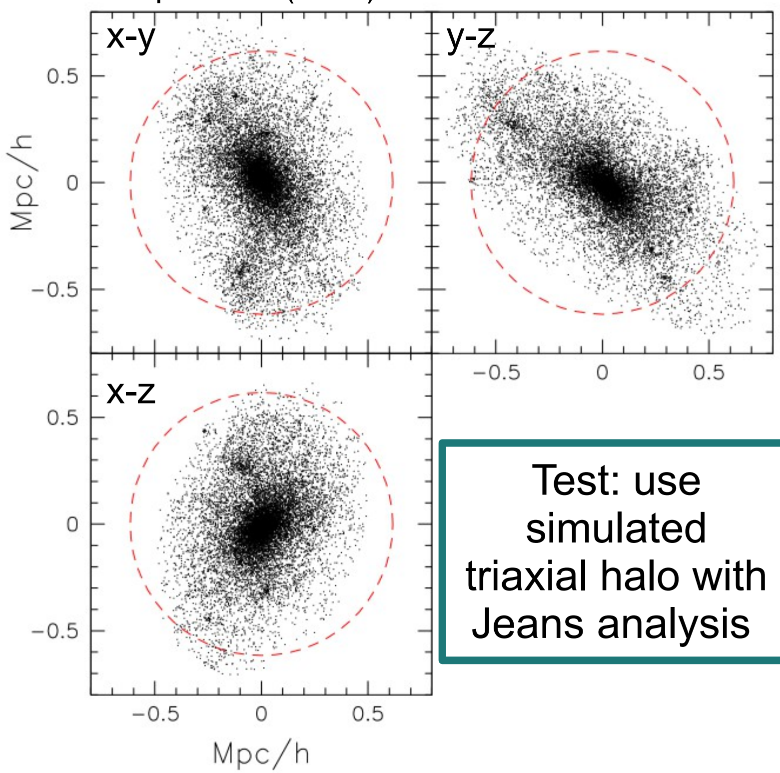
- **New Jeans module** → full analysis, from kinematic data to J-factors for dSph

Multi-level boost



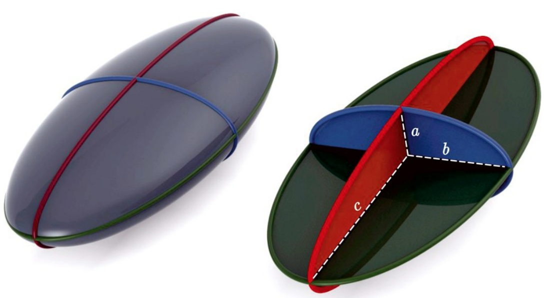
Systematics in the Jeans analysis

Despali et al (2013)



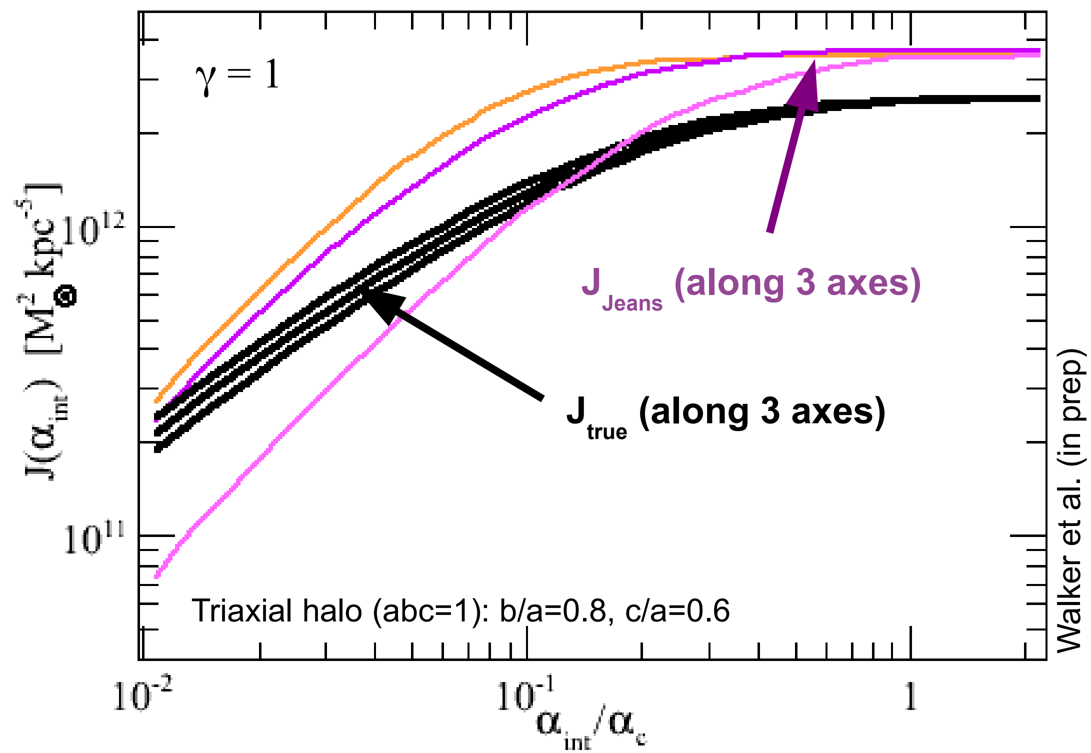
Test: use simulated triaxial halo with Jeans analysis

Haloes are triaxial



Preliminary results on triaxiality

Simulated data provided by W. Dehnen and M. Wilkinson (Univ. of Leicester)



Assuming spherical symmetry has a significant impact on the J-value reconstruction

J_{tot}, substructures, and boost factor

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

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

[up to 20% of J_{tot} in some config.]

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

[boost signal]

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

[exact realisation (mass and position) of DM distribution unknown]

Average description using mass and spatial distribution from simulations

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

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

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