Baryonic and dark matter distribution in cosmological simulations of spiral galaxies

Pol Mollitor

Laboratoire d'Astrophysique de Marseille

- arxiv:1405.4318
  in collaboration with E. Nezri (LAM), R. Teyssier (Univ. of Zurich)
- Astroparticle aspects soon on arxiv:
  +J. Lavalle, S. Magni (LUPM), L. Lellouch, C. Torrero (CPT):
  Indirect/Direct detection of dark matter, cosmic rays

Astroparticle Physics 2014:
A joint TEVPA/IDM Conference

23rd - 28th June 2014

Outline

Introduction

Dark matter only simulations:

- No baryons.
- Cusped DM profile.
- Too many satellites and too-big-to-fail problem (c.f. A. Brooks' plenary talk).

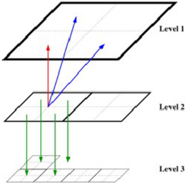
Cosmological hydrodynamic simulations until recently:

- Small disk / too massive bulge (angluar momentum problem).
- Too massive stellar disks at z=0 $\longleftarrow$ too early SFH.
- Too peaked rotation curves.

Goal of this work: $\longrightarrow$ Address this problem (with RAMSES package). (See also Guedes et al. (2011), Stinson et al. (2013), Roskar et al. (2014), Marinacci et al. (2014), Hopkins et al. (2014), Agertz & Kravtsov (2014), Vogelsberger et al. (2014), Crain et al. in prep.)
$\longrightarrow$ Use the obtained Milky-Way-like simulation as a consistent framework for astroparticle calculations (no $\pm$ ad-hoc/simplified considerations like spherical NFW profile or Maxwellian DM velocity distribution...).

RAMSES (Teyssier 2002)

This code is a grid-based hydro solver with adaptive mesh refinement.
Idea: use the Particle-Mesh algorithm on a set of adaptively refined grid.
Method:
each cell is recursively refined if the number of particles per cell exceeds some threshold.
Hydrodynamics: Godunov scheme.



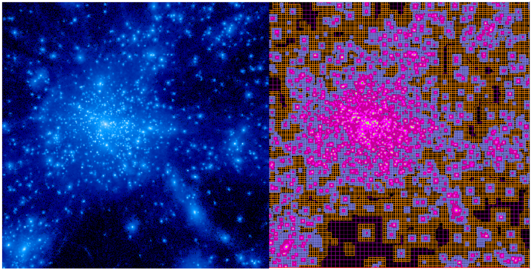


Figure : Adaptive Mesh Refinement

Star formation and supernova feedback

Star formation

- Infall of cold gas $\longrightarrow$ stars.
- Model the gas conversion into stars by a Schmidt law

$$\dot{\rho}_g = -\epsilon_{ff} \frac{\rho_g}{t_{ff}} \text{ for } \rho > \rho_0$$

with

- t_{ff} local free-fall time.
- ρ_0 threshold density, equal to density defined by gas treatment.
- ϵ_{ff} star formation efficiency, set to low value (1 %).

$\longrightarrow$Transform gas into star particles.

SN feedback:

- Type II SN, relevant for stellar masses $\approx 8 - 40 \mathrm{M}_{\odot}$.
- Short living stars.
- 10 Myr after the star (particle) creation : explosion.
- 20 % of the star mass is re-injected into the gas (corresponding to a Chabrier IMF).
- Energy per explosion $\approx 10^{51}$ erg.
- Dissipation of SN energy time scale = 20 Myrs.
- GMC model: More rare but more powerful explosions avoid an artificially concentration of SN feedback.

- Reheats the gas. Balance between star formation and SN feedback.
- Drives central dark matter density (c.f. A. Brooks' talk).
- Related to Cusp/Core question and direct/indirect dark matter detection.

Zoom simulation

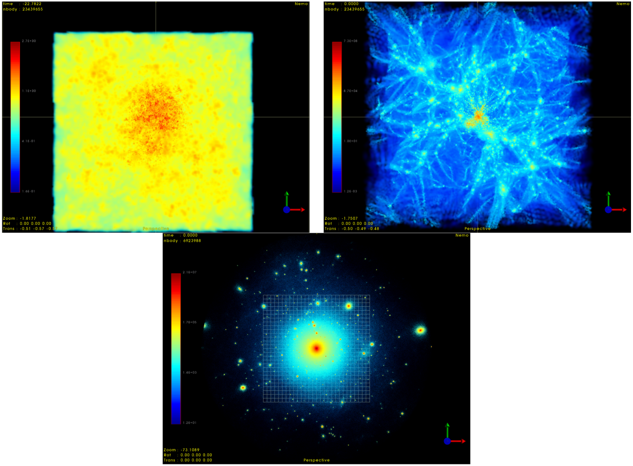


Figure : 3 Boxes showing: The primordial DM density fluctuations, the evolved structure and the zoomed DM halo.

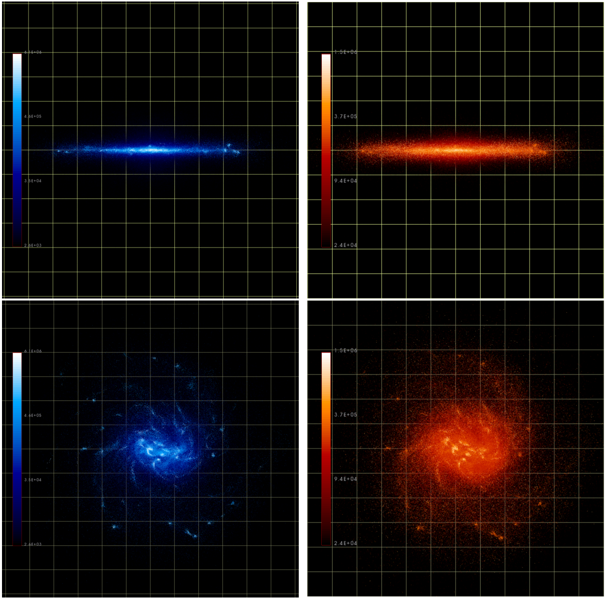
Refinement limited to high-Resolution region!

Milky Way-like Halo

Run	R_{97} (kpc)	$M_{97,\mathrm{tot}}$ (10^{10})	$M_{97,\mathrm{gas}}$ (10^{10})	$M_\star$ (10^{10})	$M_{97,\mathrm{dm}}$ (10^{10})	R_{200} (kpc)	$M_{200,\mathrm{tot}}$ (10^{10})
A	344.9	227.52	23.96	18.23	185.32	253.69	186.68
A-DM	329.28	19.79				243.53	165.13
B	233.99	71.04	7.96	5.58	57.49	176.47	62.83
B-DM	220.85	59.73				162.90	49.42
C	244.60	81.15	9.58	5.50	6.60	181.83	68.73
C-DM	236.41	73.27				176.01	62.35

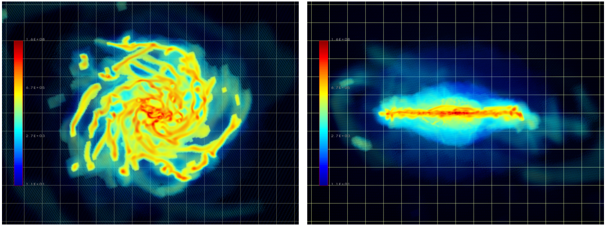
Primary numerical parameters of the simulated halos at $z = 0$, A, B and C referring to the hydrodynamical versions and *-DM to the corresponding dark matter only simulations. We show the radius of the sphere whose mean density is equal to 97 (respectively 200) times the critical density of the universe at redshift 0. The further columns give the total mass and DM mass inside R_{97}, the gas mass and stellar mass inside $R_{97}/10$. The corresponding numbers of gaseous cells, star particles, and DM particles are given next. In all the runs, the spatial resolution reaches 150 parsec at $z = 0$.

Halo B: the stellar galaxy maps

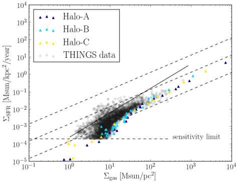


Projected stellar luminosities for Halo B at redshift 0 in U-band (blue) and K-band (red).

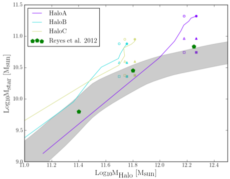
Galaxies at redshift 0



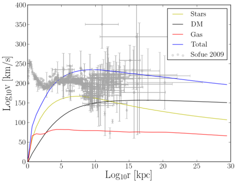
Upper panel: Face-on and side-on view on the gas density disk of Halo B.



Kennicutt-Schmidt relation.



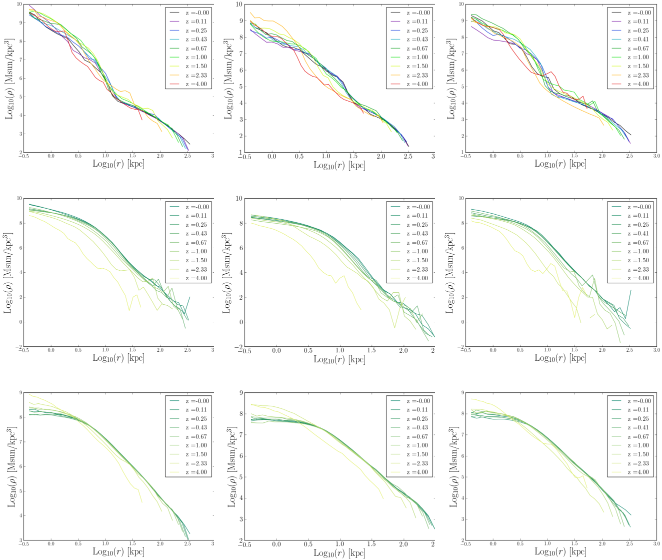
Galactic stellar mass relative to halo mass evolution.



Rotation curve for Halo B.

Density profiles for the three halos over redshift

- Hydro Run density profiles.



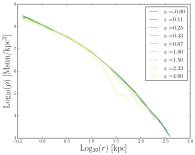
Gas

Stars

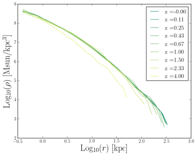
DM

Halo A Halo B Halo C

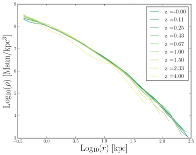
- DM-only Run: dark matter profile



Halo A



Halo B



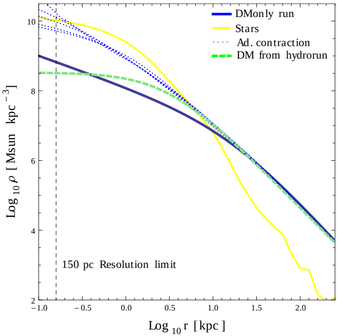
Halo C

- Best fitting values for the spherical averaged density profiles fitted with equation $\rho(r, \rho_s, r_s, \alpha, \beta, \gamma) = \frac{\rho_s}{(\frac{r}{r_s})^\gamma (1+(\frac{r}{r_s})^\alpha)^{(\beta-\gamma)/\alpha}}$. For the DM-only simulations, we fixed $\alpha = 1$. The fit was performed for $r \in [250\mathrm{pc}, \mathrm{R}_{97}]$.

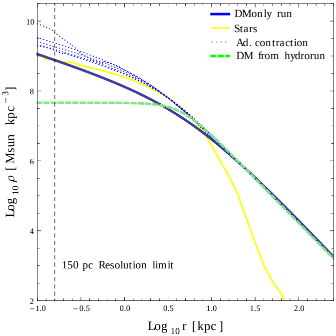
Run	$\mathrm{Log}_{10}\rho_s$ [/kpc^3]	r_s [kpc]	α	β	γ
Halo A	8.005	4.39	1.879	2.469	0.126
Halo A-DM	7.232	13.026	1	2.707	0.794
Halo B	7.663	4.425	2.895	2.541	~ 0
Halo B-DM	7.639	5.552	1	2.636	0.819
Halo C	7.678	4.317	2.451	2.477	0.268
Halo C-DM	6.992	13.148	1	2.871	0.927

Adiabatic Contraction

DM profile from DMonly simulation contracted via a model calibrated (Blumenthal et al. 1986) on cosmological simulations (Gnedin et al. 2004) by the stellar profile obtained in the hydro run.



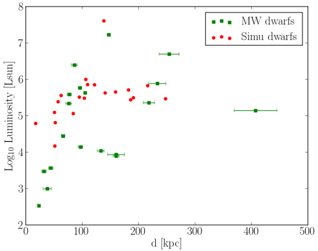
Halo A

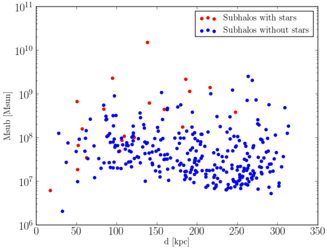


Halo B

- Cusp/core transformation (Pontzen & Governato (2012) arXiv:1106.0499, Brooks & Zolotov (2014) arXiv:1207.2468, Maccio et al. (2012), Teyssier et al. (2013) arXiv:1206.4895).
- And : Adiabatic contraction at r$\sim 5 - 10$ kpc.
- Core formation is not observed for this stellar galactic mass range in MagiCC simulations (di Cintio et al. 2014 arXiv:1306.0898) and not at all in simulations performed with AREPO (Marinacci et al. 2014 arXiv:1305.5360).

Satellites: Halo B





- Left panel: Comparison between the luminosity from the simulation subhalos with the dwarfs in the Milky Way.
- Right panel: Masses with respect to their distance to the halo center of luminous and dark satellites in the simulation.
- Removes tension from the missing satellites and the too-big-to-fail problem (c.f. di Cintio et al. 2011 arXiv:1107.5045).

See also Sawala et al. (2014) arXiv:1406.6362.

Dark matter detection aspects.

Direct detection

The dark matter results of the simulation = Realistic and consistent Milky-Way-like framework for astroparticle calculations!

$$\frac{dR}{dE_R} = \frac{\rho_{\mathrm{DM}}}{M_{\mathrm{DM}}} \frac{d\sigma}{dE_R} \eta(E_R, t)$$

Particle and nuclear physics:

$$\frac{d\sigma}{dE_R} = \frac{M_N}{2\mu_n^2} \sigma_n^0 \frac{(f_p^2 Z + (A - Z) f_n^2)^2}{f_n^2} F^2(E_R)$$

Astrophysics:

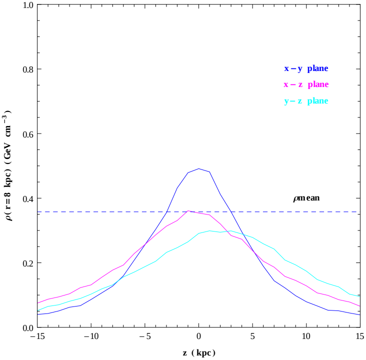
$$\eta = \int_{vmin}^{vescape} d^3\vec{\nu} \frac{f(\vec{\nu})}{|\vec{\nu} - \vec{\nu}_{\mathrm{earth}}|}$$

Features?
Maxwellian?
vmin? vescape?

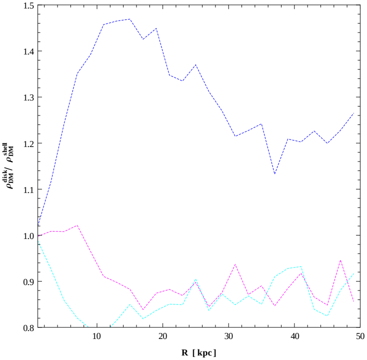
See Vogelsberger et al. (2009) arXiv:0812.0362, Ling et al. (2010) arXiv:0909.2028, Pillepich et al. (2014) arXiv:1308.1703, Read (2014) arXiv:1404.1938.

Local dark matter density

Dark Disk? Related to direct DM detection.
Under investigation...



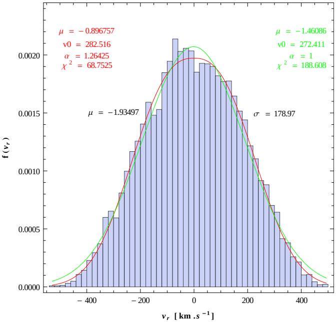
Density at 8 kpc in different planes.



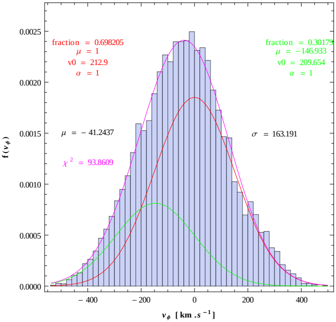
Ratio of the density in a disk over the spherical shell of different planes.

Local dark matter velocity distribution

In the galactic reference frame:

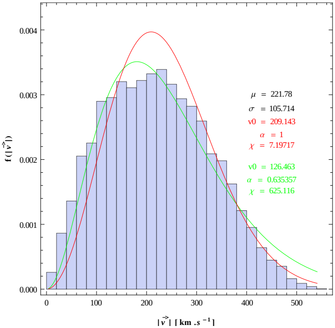


Dark matter radial velocity. (Gaussian Fit: Green / Generalized Gaussian Fit: Red)



Dark matter tangential velocity (Double gaussian component fit: Magenta / 1rst Gaussian fit: Red / 2nd Gaussian fit: Green).

Local Dark matter vel. distribution

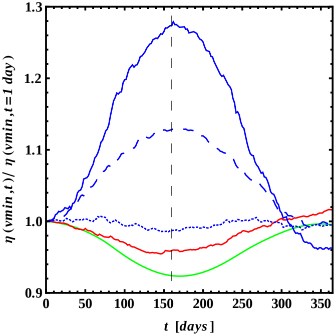


Modulus of dark matter velocity (Maxwellian Fit: Green / Generalized Maxwellian Fit: Red)

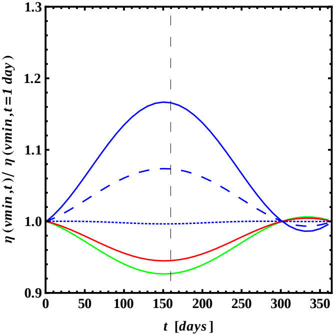
Eta term

Eta term: annual modulation for the simulation data and the Maxwellian fit.

vmin = (0 Green, 100 Red, 200 Blue Tiny Dashed, 300 Blue Large Dashed, 400 Blue Joined) km/s.



Eta term modulation seen over a year for different integration limits for the simulation data.



Same plot for the Maxwellian fit.

Indirect Detection

$$\frac{d\Phi_{\gamma,\nu}}{d\Omega} = \frac{1}{4\pi} \underbrace{\frac{1}{\delta}\frac{\langle \sigma v \rangle}{m_D^2 M} \int_{E_{min}^{\gamma,\nu}}^{E_{max}^{\gamma,\nu}} \sum_i \frac{dN^i_{\gamma,\nu}}{dE_{\gamma,\nu}} BR_i}_{\text{HEP}} \underbrace{\int_{l(\vec{\Omega})} \rho_{DM}^2 dl}_{\text{Astro}}$$

Particle physics

- Annihilation cross section
- Dark matter mass
- Annihilation induced spectra

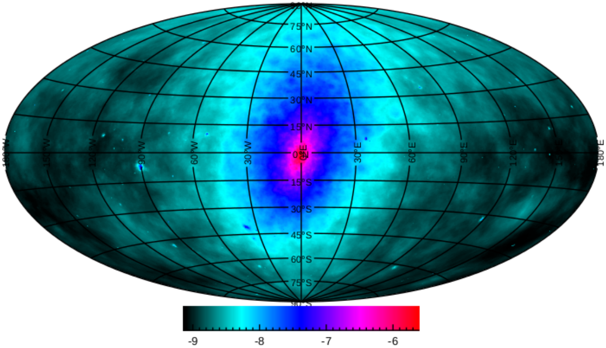
Astrophysics:DM distribution

- Features ?
- Cusp ?
- Clump features ?
- Baryons ? (compression ?)
- Feedback ?

See Stoehr et al.(2003) arXiv:astro-ph/0307026, Kuhlen et al.(2008) arXiv:0805.4416, Springel et al.(2008) arXiv:0809.0894, Athanassoula et al. (2009) arXiv:0801.4673, Nezri et al.(2012) arXiv:1204.4121.

Indirect Detection

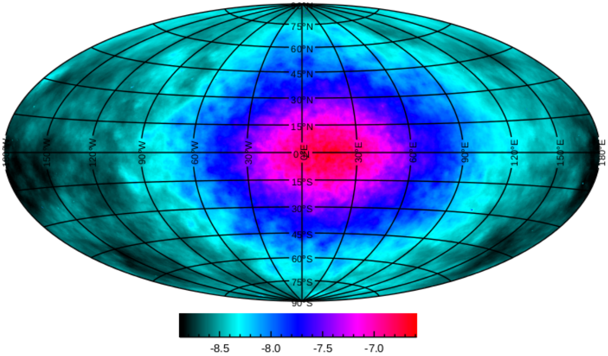
Dark matter only simulation:
Gamma skymap of annihilating DM.



- WIMP: $M_{DM} = 100$ GeV, $b\bar{b}$, $< \sigma v >= 3 * 10^{-26}$ cm^3/s
- Observer at 8 kpc.

Indirect Detection

Simulation with hydrodynamics:
Gamma skymap of annihilating DM.



- WIMP: $M_{\rm DM} = 100$ GeV, $b\bar{b}$, $<\sigma v>= 3 * 10^{-26}$ cm^3/s
- Central DM profile is cored (Feedback...)
- Detectability depends on background.

Indirect Detection

Background model for cosmic rays: Use SN feedback, star and gas distribution to calculate diffuse hadronic gamma emission.
Star distribution $\rightarrow$ SNII explosion $\rightarrow$ cosmic rays.
Gas distribution $\rightarrow$ CR spallation $\rightarrow$ gamma fluxes.

SN feedback

- IMF 20% $\rightarrow$ massive stars.
- Age $=$ 10 Myr (Type SN II).
- Energy per explosion : 10^{51} erg.
- 20% used as feedback energy.

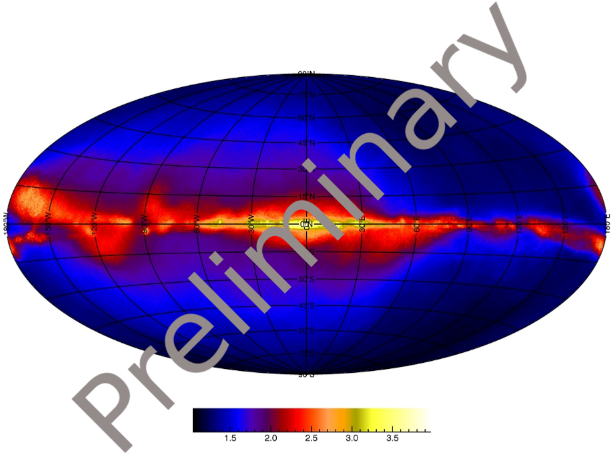
SN II $=$ Cosmic Ray sources

- Select all SN events in the past 500 Myr (typical residence time of CRs in the Galaxy).
- Explosion rate (at redshift 0) $\sim$ 4 Msun/year.
- 10% converted into high energy cosmic rays with a power law energy spectra : E^{-2}.

See Nezri et al. (2012) arXiv:1204.4121.

Indirect Detection

Background model for cosmic rays
Gamma skymap: In progress...



Disc morphology -> to be compared with Fermi.

Conclusions

Summary:

- Zoom simulations with RAMSES.
- One halo/galaxy exhibits a lot of MW observational properties.
- Interplay between star formation and SN feedback → Impact on dark matter profile (we obtained a cored DM profile).
- Caveat with star formation history → need for a different/additional feedback scheme?
- Local dark matter: Adiabatic contraction and corotating dark disk.
- Analyse of satellites: Halo in lower MW mass range seem to agree with MW observations.

Perspectives:

- Improvement of spiral galaxy simulations: new (more exact) treatment of gas physics intervening in star formation or (and?) new feedback schemes?
- Consistent framework for astroparticle calculations related to (direct and indirect) dark matter detection.