N-body simulations and dark matter detection

N-body :

See e.g : Keres et al arXiv:1109.4638
arxiv:1004.0005, Agertz, Teyssier, Moore
Governato et al arxiv:0911.2237, arxiv:1106.0499
review : arxiv:0801.1023, Dolag et al

links between N-body simulations and dark matter detection:

Gamma signal and background (arxiv:11xx.xxxx in progress)
Direct detection (arxiv:0909.2028)
Cosmic rays (arxiv:0808.0332)
Gamma and neutrino indirect detection (arxiv:0801.4673)

Collaboration with J. Lavalle, F.-S. Ling, R. Teyssier, L. Athanassoula

See also e.g :
Aquarius : gamma (arXiv:0809.0894),Direct detection (arXiv:0812.0362)
Via Lactea gamma (arXiv:0805.4416)
...

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GDR Terascale, CPPM Marseille. 12 october 2011

Outline

- **N-body simulations : some basics**
- **Features of dark matter halos and disk galaxies**
- **Consequences for dark matter detection**

Introduction

Hierarchical structure formation scenario

- Comological parameters : $\Omega_\Lambda, \Omega_M, \Omega_b, \sigma_8, H_0, h.$

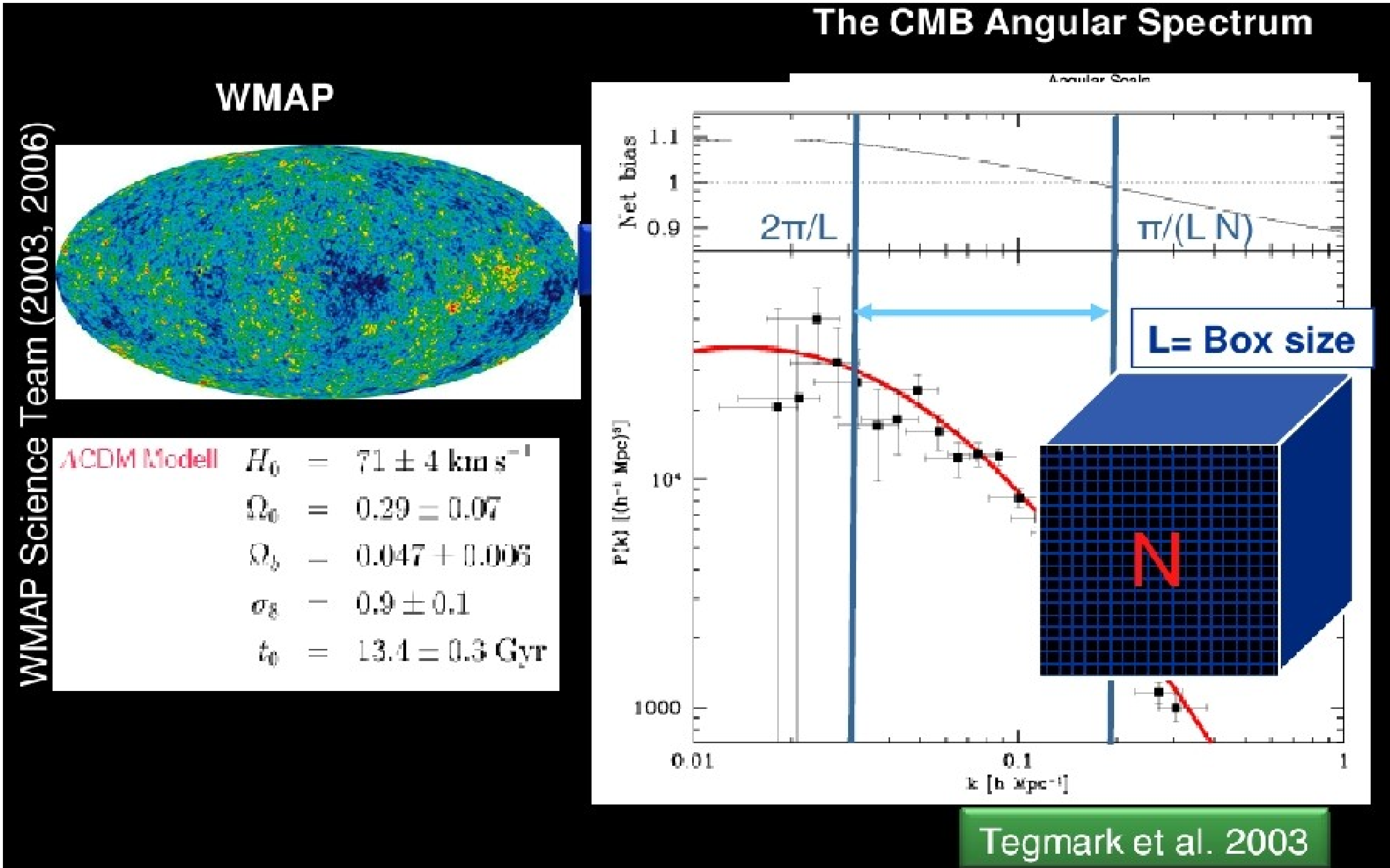
- Size of the box

- Computer capacity $\Rightarrow$ Nb of particles

$\Rightarrow$ Mass of dark matter particles $\sim 10^{3-5} M_\odot$

Introduction

Initial conditions given by CMB power spectrum : WMAP



Physics

DARK MATTER (and STARS)

- **Gravity : Vlasov and Poisson equations**

$$\nabla^2\Phi = 4\pi G\left[\rho + (n-2)\rho_X\right]$$

GAS

- **Hydrodynamics : Euler equations**
- **+ Gravity**

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho \boldsymbol{u}) = 0,$$

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\nabla)\boldsymbol{u} = -\nabla\Phi - \frac{\nabla p}{\rho},$$

$$\frac{\partial \varepsilon}{\partial t} + \boldsymbol{u}\cdot\nabla\varepsilon = -\frac{p}{\rho}\nabla\cdot\boldsymbol{u},$$

Physics

DARK MATTER (and STARS)

- **Gravity : Vlasov and Poisson equations**

Solved by N-body techniques :
i.e “particles”

GAS

- **Hydrodynamics : Euler equations**
- **+ Gravity**

2 approaches :

- **Lagrangian : fluid=particles (SPH)**
  GADGET code (V.Springel)
- **Eulerian : fluid=grid (AMR)**
  RAMSES code (R.Teyssier)
- **“Hybrid”**
  AREPO (V.Springel)

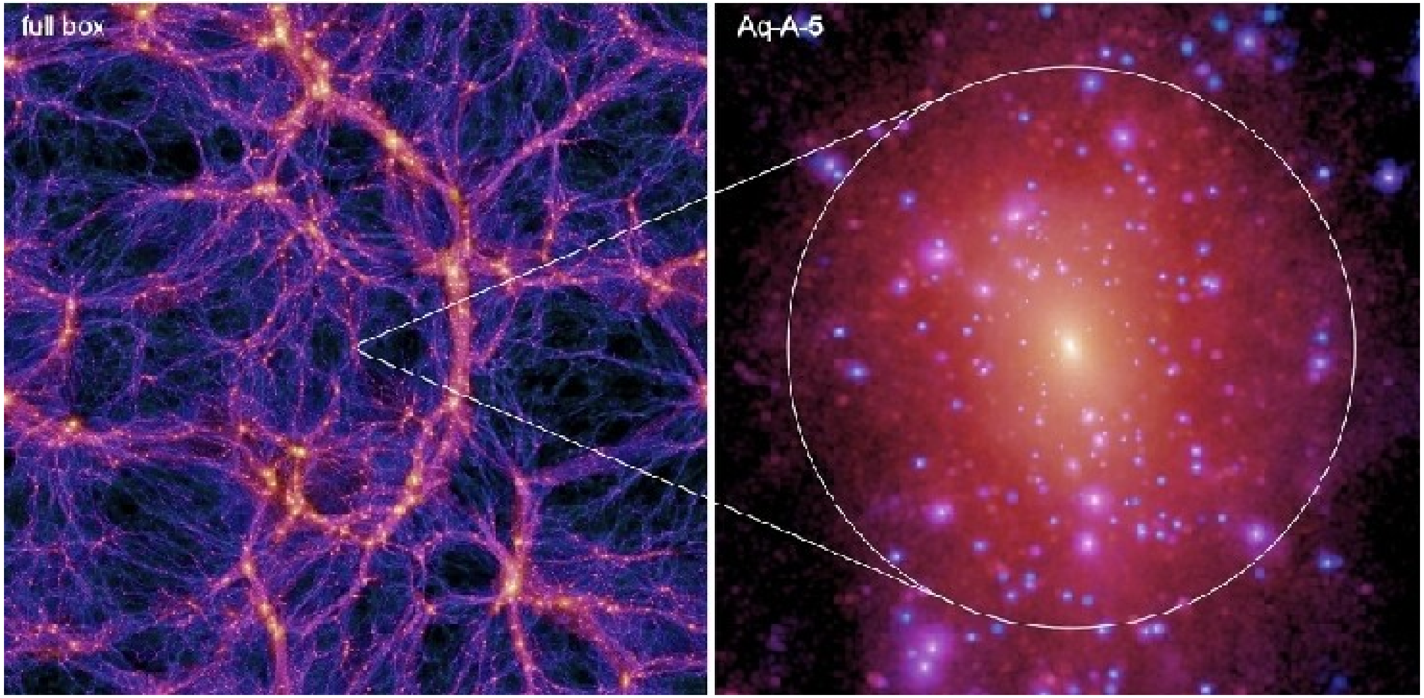
Some results

- **NFW, VIA LACTEA I&II, AQUARIUS, GHALO, HORIZON, CLUES, BOLCHOI ...**

DARK MATTER only simulations :

- **Describe well large scale structure formation : filaments**
- **Give non smooth dark matter distribution : presence of virialized (sub)structures (agreement with Press-Schester, Sheth-Tormen)**

= CLUMPS



AQUARIUS, Springel et al 2008

Some results

- **NFW, VIA LACTEA I&II, AQUARIUS, GHALO, HORIZON, CLUES ...**

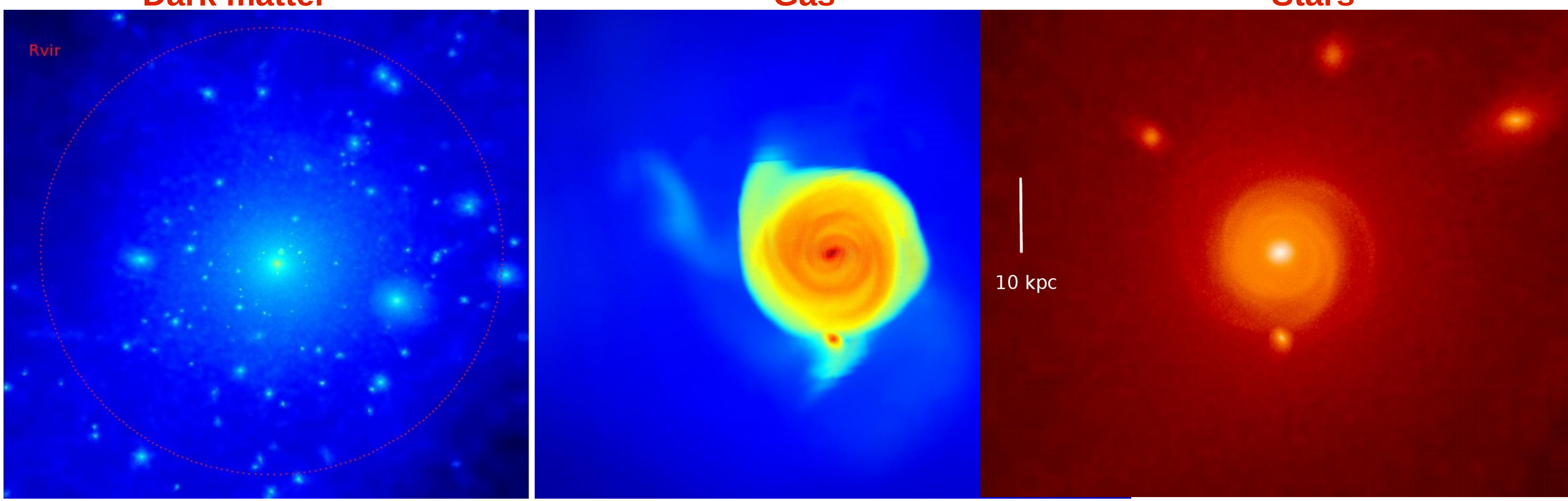
Simulations including gas :

- **Filaments**
- **CLUMPS**

- **Gas accreted in DM potential**

  → Disk and stars formation

Dark matter **Gas** **Stars**



HORIZON project simulation by R.Teyssier

Pictures with Glnemo viewer (Jean-Charles.Lambert@oamp.fr)

Star formation : recipe

- **Infall of cold gas → stars**

- **Model the gas conversion into stars by a Schmidt law**

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

- **t_{ff} free-fall time**
- **$\rho 0$ threshold density**
- **ε_{ff} drive star formation rate**

→ Transform gas into star particles

Supernovae feedback

- **Type II SN, relevant for stellar masses ~** $8\text{–}40\ \mathrm{M}_\odot$
- **Represents ~ 10 % of the mass of a stellar population**
- **Short lived stars**
- **~ 10-20 Myr after the star (particle) creation : explosion**
- **~ 10 % of the star (particle) mass is re-injected into the gas**
- **Energy per explosion** $E_{\mathrm{SNII}} = 10^{51}\ \mathrm{erg}$

→ **reheat the gas, can regulate star formation rate**

Clumpy dark matter halos

- **Dark matter distribution not smooth : clump spectrum**

$$\frac{dN_{cl}}{dM} \propto \left(\frac{M}{M_H}\right)^n$$

typically $n \sim -1.8 - 2$

Problem :

Number of satellites > observations … new dwarf galaxies to be discovered ? … in progress
satellites whitout gas and stars (photoionisation, SN feedback)?

(Cuspy ?) Dark matter Halos

Fit of N-body results :

- **Cusps**

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

$$\rho_{DM}(r) \propto r^{-\gamma} \quad \text{(small } r\text{)}$$

- ⋆ NFW 1997 : $\gamma = 1$
- ⋆ Moore et al 1999 : $\gamma = 1.5$
- ⋆ VIA LACTEA (I and II), Diemand et al 2006-2008 : $\gamma = 1.2$

- **Einasto (AQUARIUS)**

$$\rho_D M(r) = \rho_{-2} e^{-\frac{2}{\alpha}[(r/r_{-2})^{\alpha}-1]}$$

But : Observations suggest cored profiles, i.e $\gamma = 0$

Baryon impacts on dark matter halo

Dark matter profile steepened or flattened by baryon processes

- **Adiabatic compression : Blumenthal et al 1986**

Angular momentum and mass conservation : $M_i(r_i)r_i = [M_b(r_f) + M_{DM}(r_f)]r_f$

- ⋆ $M_i(r)$: mass profile of the galactic halo before the cooling of the baryons
- ⋆ $M_b(r)$: the baryonic composition of the Milky Way observed now
- ⋆ $M_{DM}(r)$: the dark matter component of the halo today (determined iteratively)

$$\text{NFW} : \rho_{DM}(r) \propto r^{-1} \rightarrow r^{-1.5}$$

- **ISM physics : stellar formation, SN feedback …**

- The response of the DM halo is driven by the history of assembly of baryons into a galaxy : *Pedrosa et al* : arxiv:0902.2100

- ISM carefull treatment could lead to shallow profiles on dwarf scale *Governato et al* arxiv:0911.2237,Pontzen& Governato arxiv:1106.0499

- **Dark disc : clump accretion by stellar and star disc … *Read et al* 0902.0009**

→ enhancement of DD signal ?
capture rates in the Sun ? *Bruch et al 2009 vs Ling 2010*

Still debated ...

CDM Cosmological simulations

Cosmological N-body simulations with gaz : successful tool for disc galaxy formation, works well qualitatively

- **Nb and dynamics of satellites**
- **Cusp/Core** (*Governato et al* arxiv:0911.2237,Pontzen,Governato arxiv:1106.0499)
- **Angular momentum problem**

(bulges too dominant, discs not extended enough)

(Agertz, Teyssier, Moore arxiv:1004.0005, Keres et al arxiv:1109.4638)

- **Improvement of ISM physics treatment**

Realistic and consistent Milky-Way like framework for astroparticle calculations ...

NFW : Navarro Frenk and White … Frenk supports warm dark matter
arxiv:1104.2929, arxiv:1105.3474
http://www.bbc.co.uk/news/science-environment-14948730

Direct detection

Rate :

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

Particle and nuclear physics

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

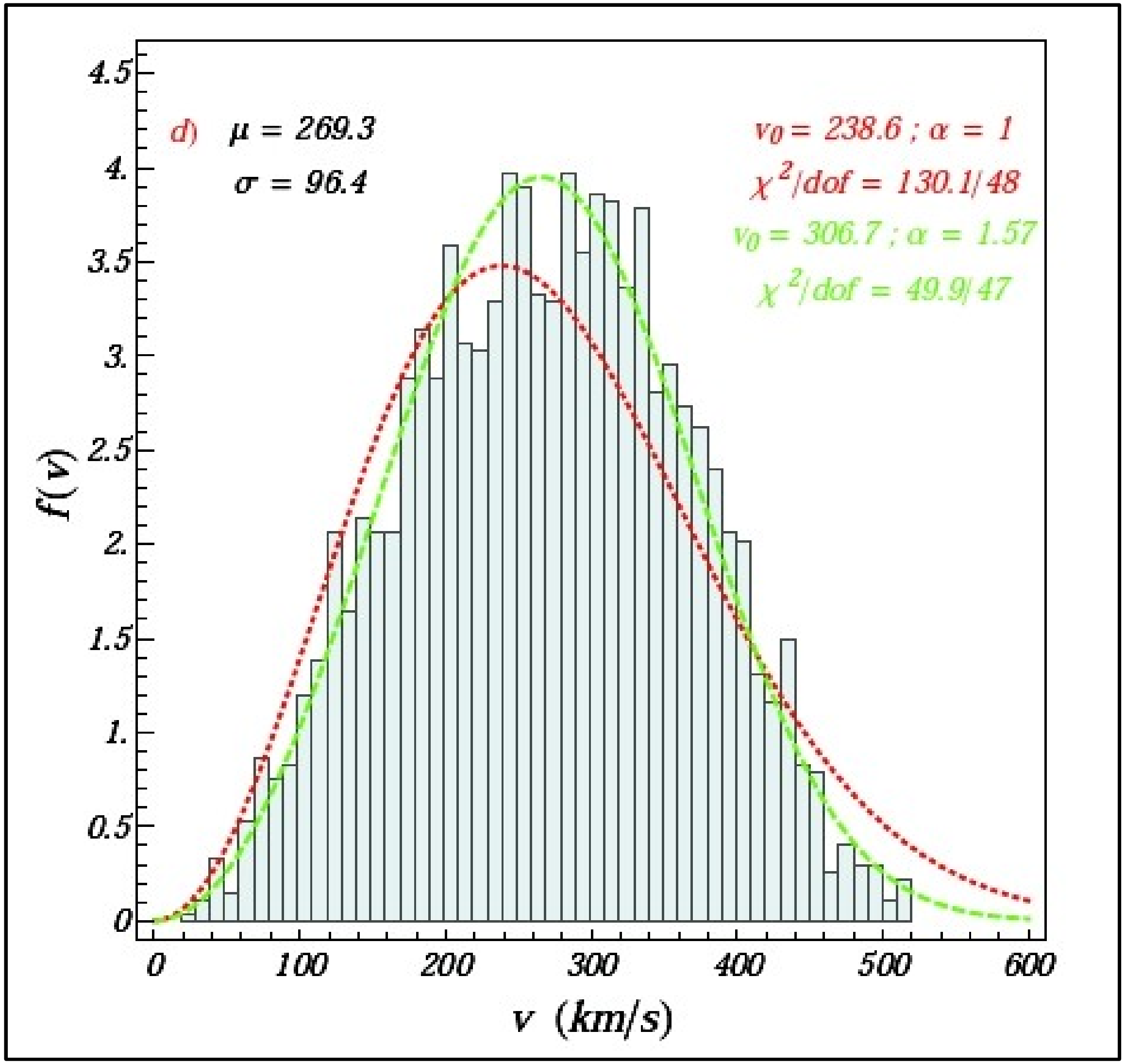
Astrophysics

$$\eta = \int d^3\vec{v} \, \frac{f(\vec{v})}{\left|\vec{v} - \vec{v}_{\oplus,G}\right|}$$

Features ≠ Maxwellian ?
Dark disk ?
Corotation ?
Local density ?

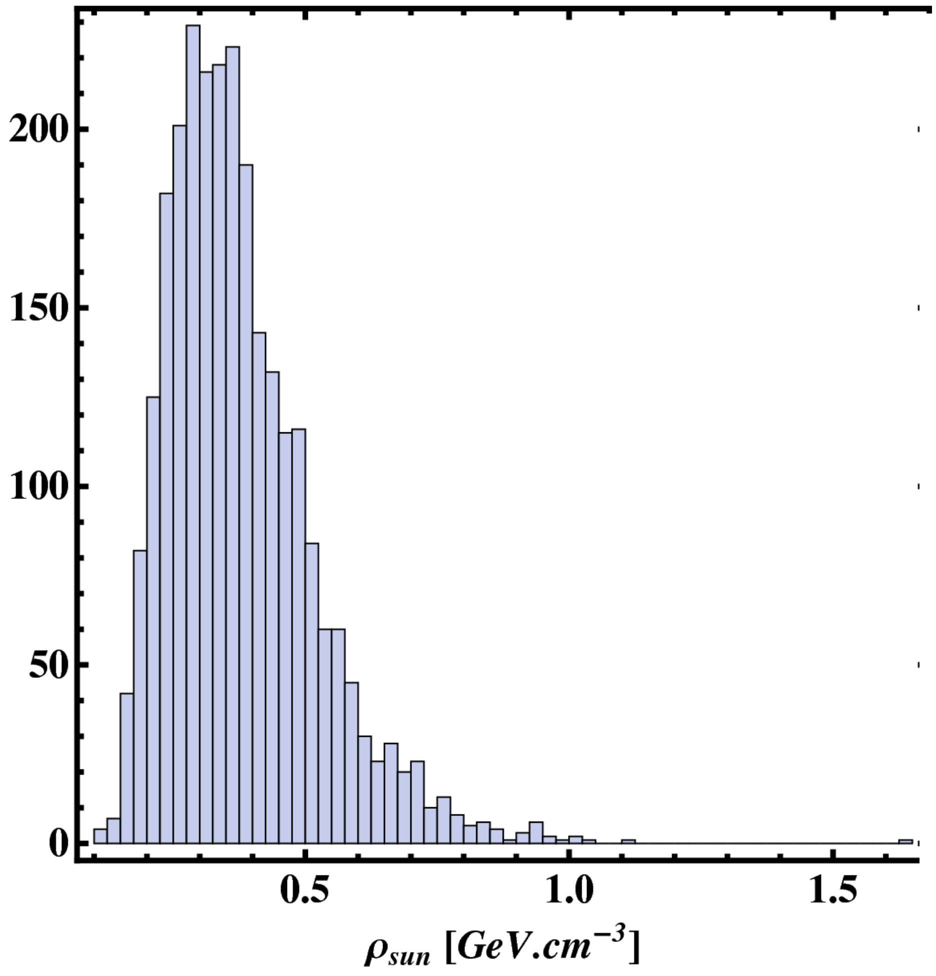
ρDM : Local dark matter density +

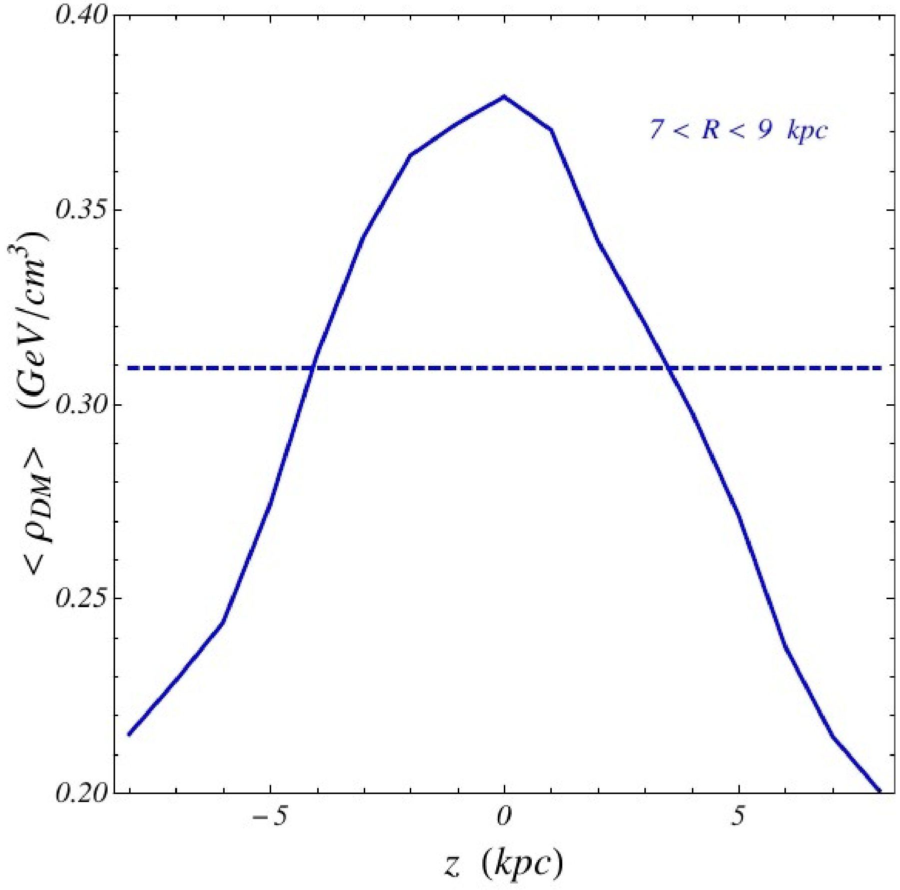
Dark matter velocity distribution



Signature on direct detection signals

Local DM density, Dark disk ?

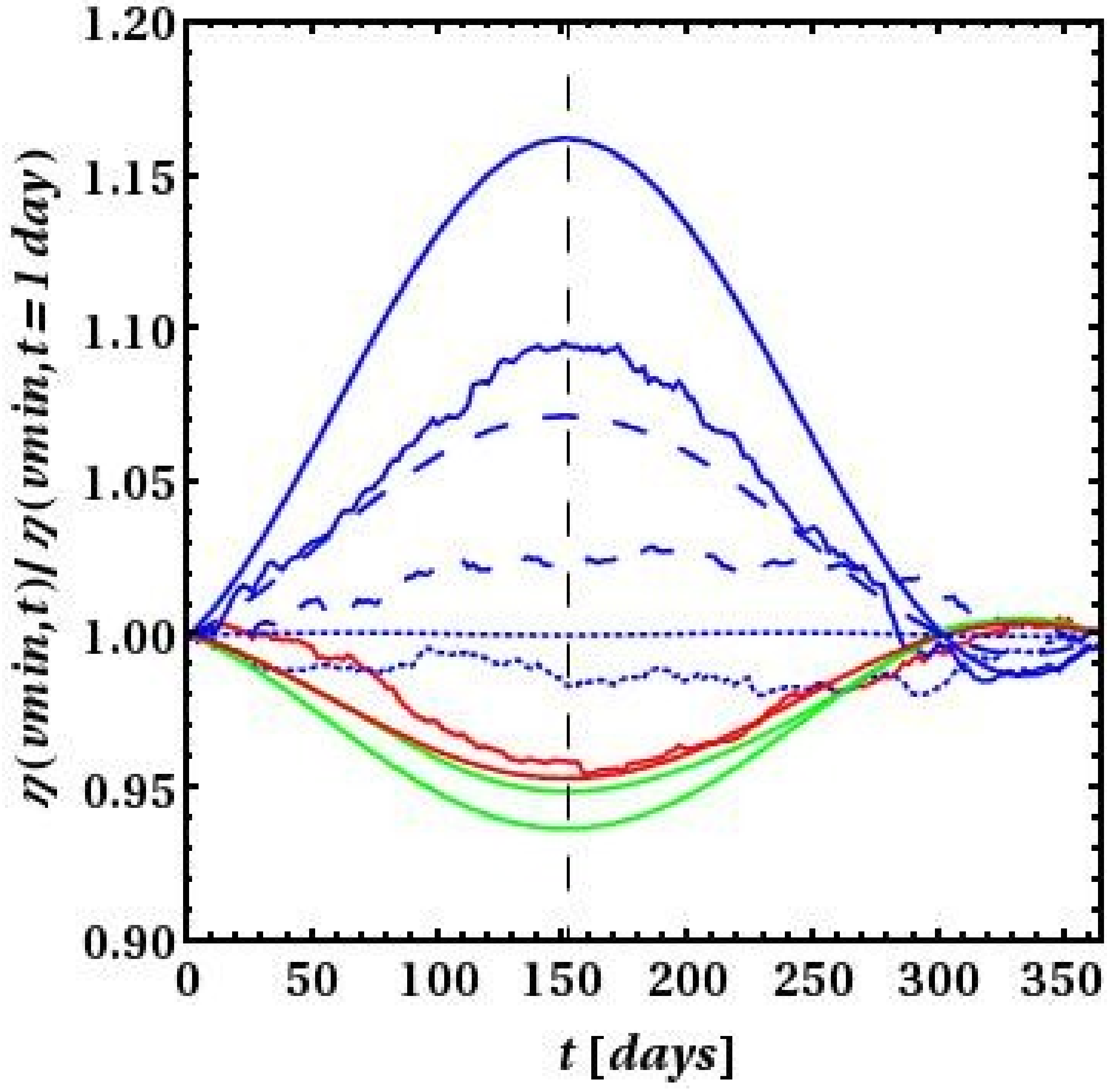




Mean(ρ_{sun}) > 0.3 GeV.cm3

Enhanced direct detection signal

Direct detection modulation



Modulation depends on velocity distribution : Maxwellian versus simulation

Directionnal direct detection could distinguish velocity distribution …
in progress collab with J. Billard, F. Mayet (Mimac)

Gamma/neutrino indirect detection

$$\frac{d\Phi_{\gamma,\nu}}{d\Omega} = \frac{1}{4\pi} \underbrace{\frac{1}{\delta}\frac{\langle\sigma v\rangle}{m_{DM}^2} \int_{E_{min}^{\gamma,\nu}}^{E_{max}^{\gamma,\nu}} \sum_i \frac{dN_{\gamma,\nu}^i}{dE_{\gamma,\nu}} BR_i}_{\doteq HEP_{\gamma,\nu}} \underbrace{\int_{l(\vec{\Omega})} \rho_{DM}^2 \, dl}_{\doteq ASTRO} ,$$

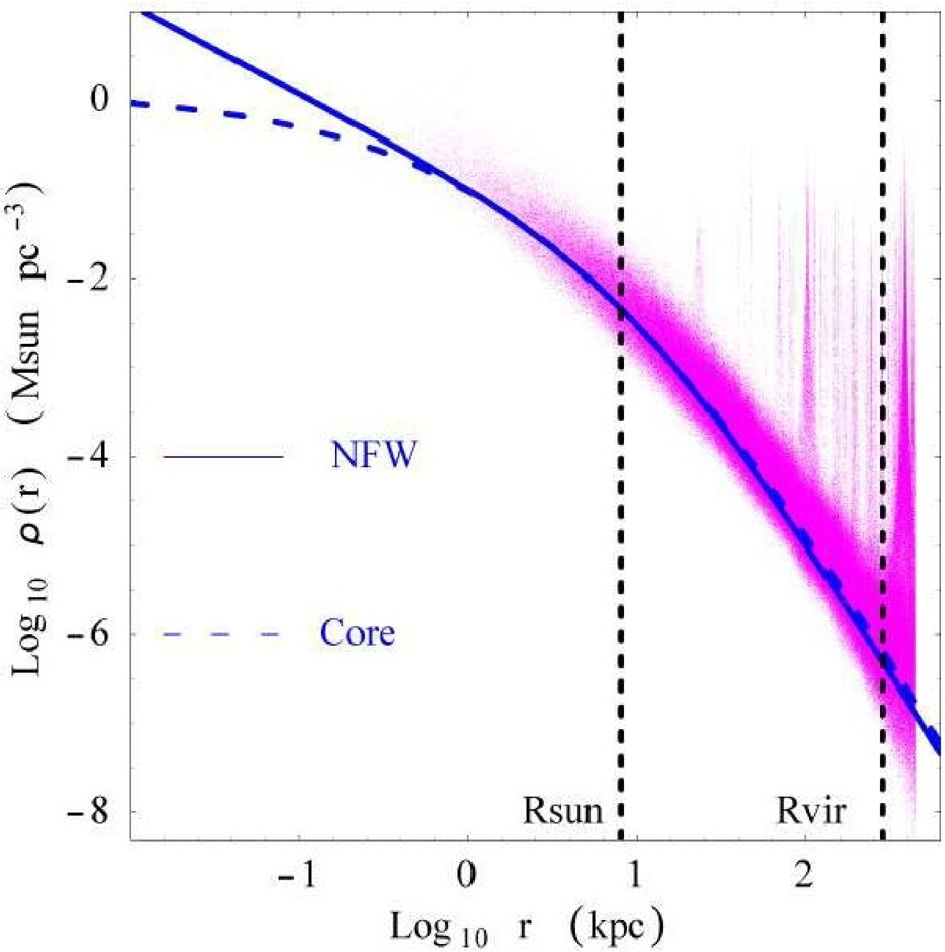
Particle physics **Astrophysics**

Annihilation cross section
Dark matter mass
Annihilation induced spectra

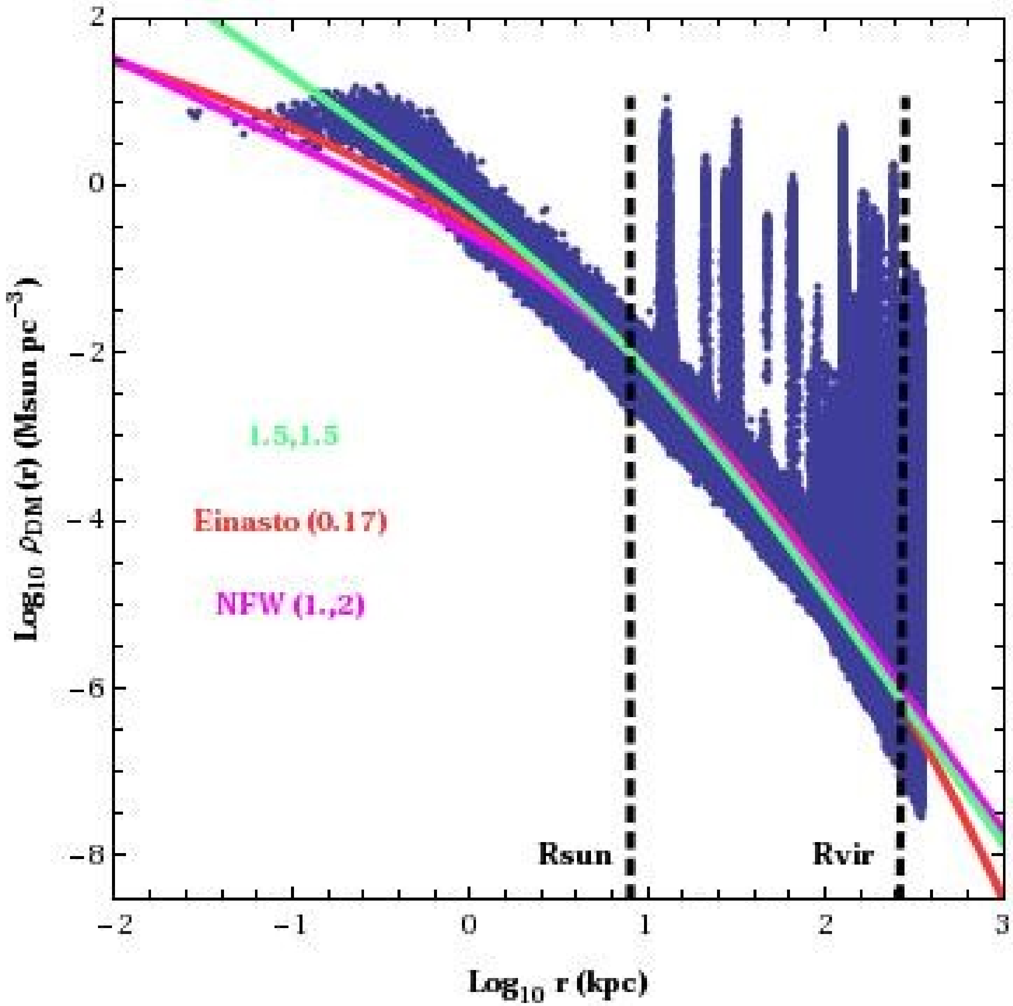
DM distribution:

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

Dark matter density :



Dark matter only



Dark matter+ baryons

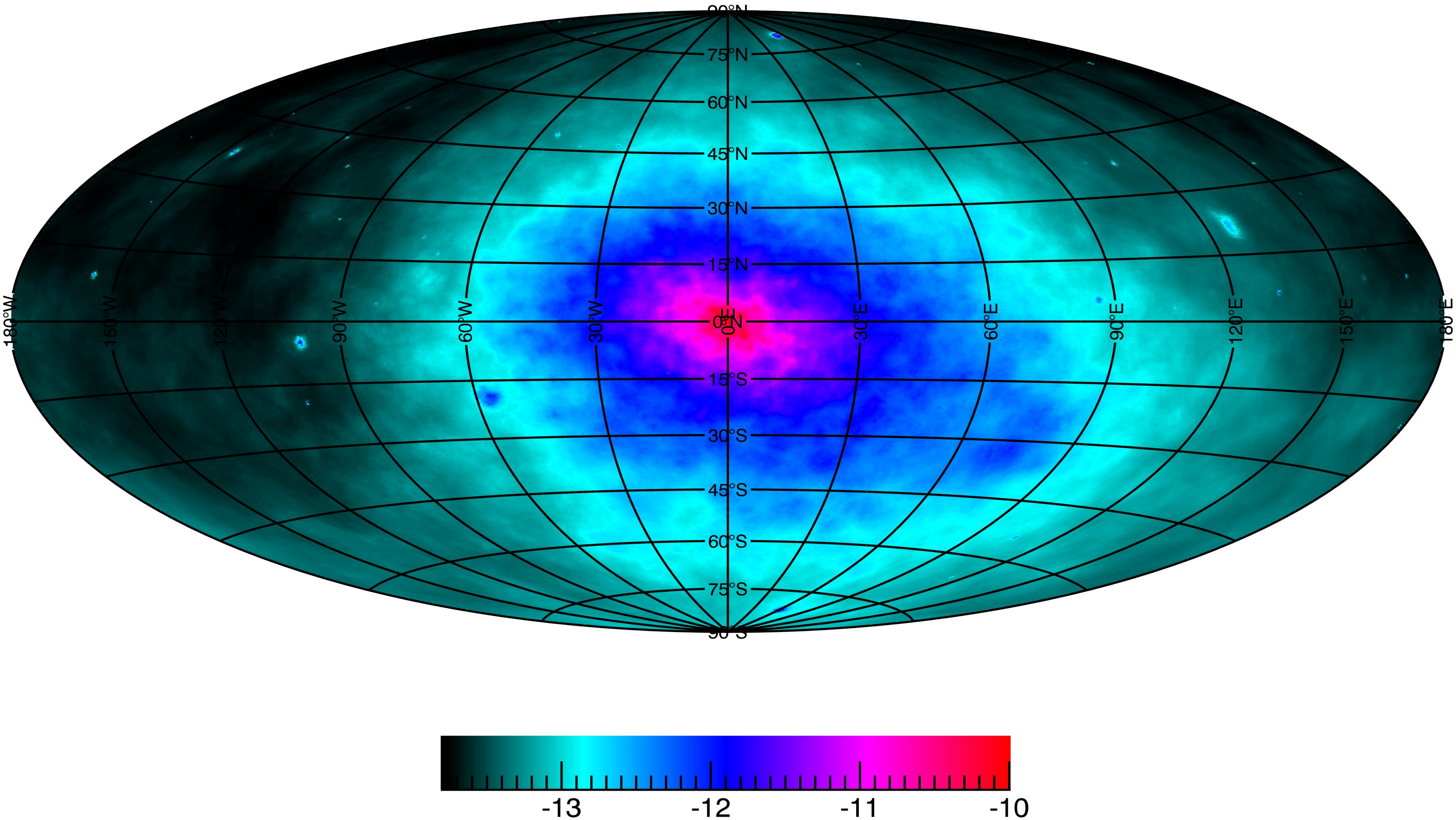
Adiabatic compression

Strong cusp

Simulations from the HORIZON project,
AMR RAMSES code (R. Teyssier)

Gamma skymap : Dark matter contribution

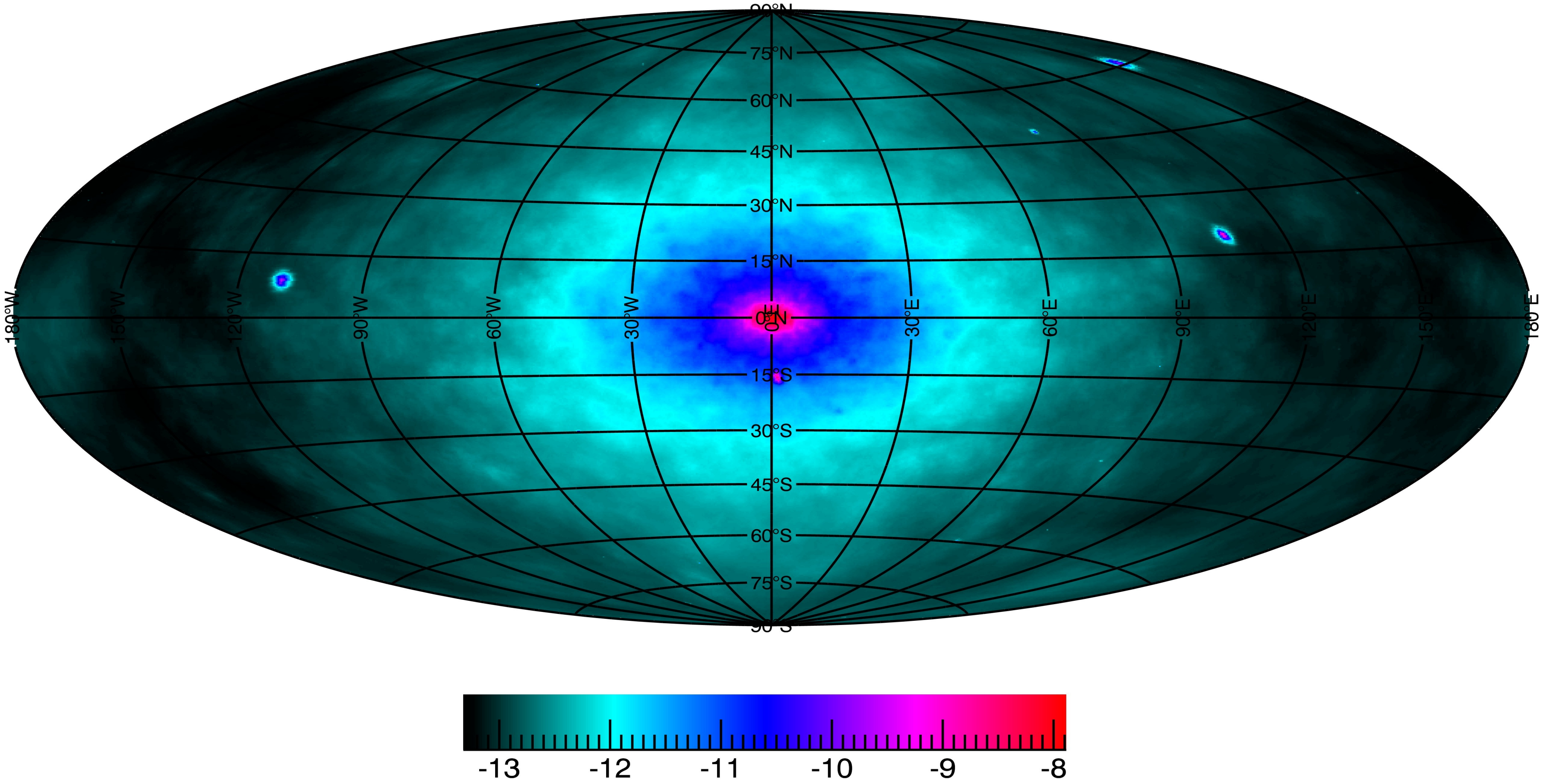
N-body simulation : dark matter only



+ standard thermal (HEP+cosmo) scenario
Gammas : FERMI,HESS ~ -10
Neutrinos : KM3Net GC ~ -9

arxiv:0801.4673

Gamma skymap : Dark matter contribution
N-body simulation : dark matter + baryons



~ 2 orders of magnitude higher fluxes in central region

Very high astrophysics contribution → HEP scenarios

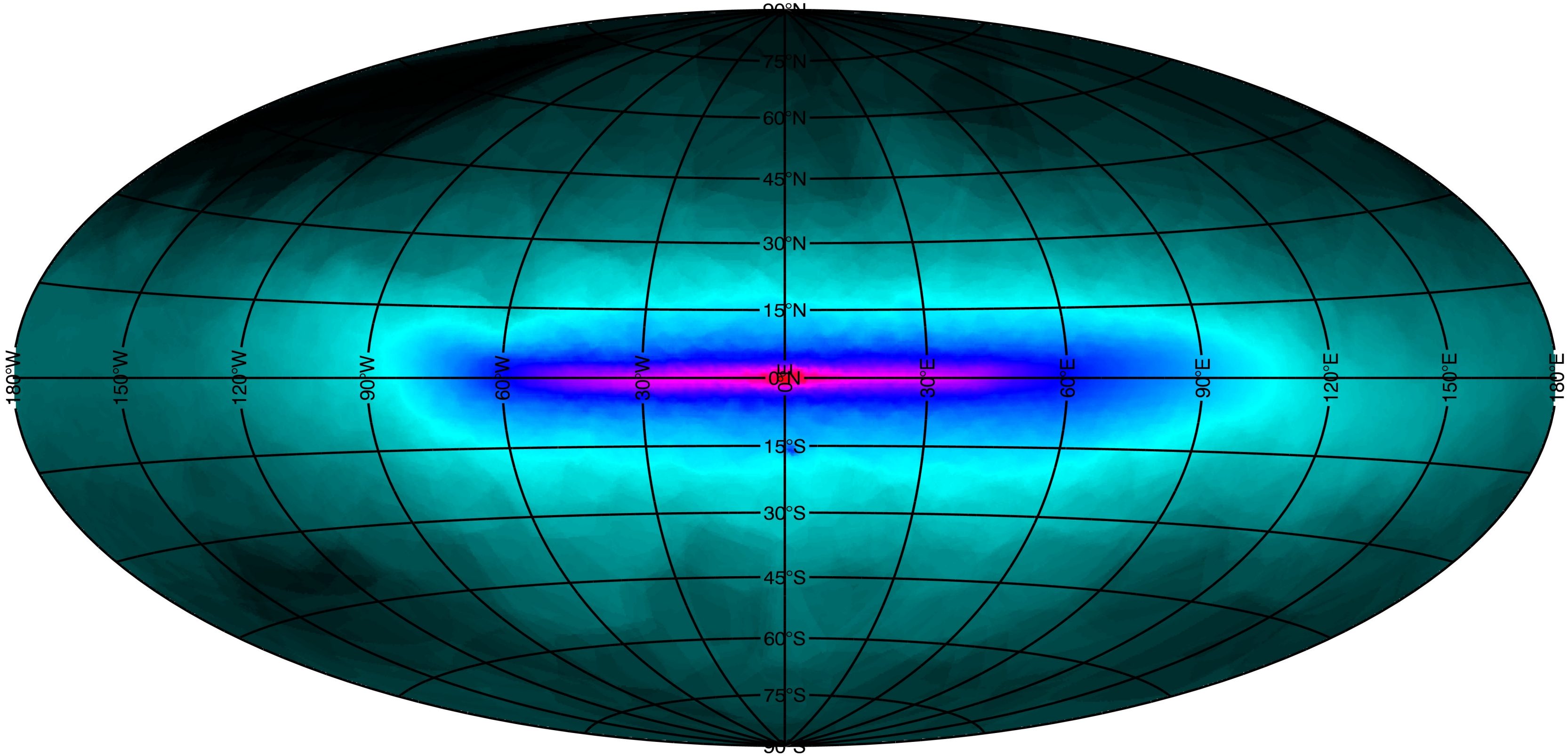
Possible conflict with observations FERMI, HESS ...

Depend on background …

Nezri, Lavalle, Teyssier … soon on arxiv

Gamma skymap : π0 Background

N-body simulation : dark matter + baryons



star distribution → SNII explosion → cosmic rays
Gas distribution → CR spallation → gamma fluxes

To be compared with Fermi ...

Nezri, Lavalle, Teyssier … soon on arxiv

Cosmic rays

collaboration with J. Lavalle

$$\vec{\nabla}\left[K(E)\vec{\nabla}\mathcal{N}_{\rm cr} - \vec{V}_{\rm conv}\mathcal{N}_{\rm cr}\right] + \frac{\partial}{\partial E}\left[b(E)\mathcal{N}_{\rm cr} + K_{EE}\frac{\partial}{\partial E}\mathcal{N}_{\rm cr}\right] + \Gamma(E)\mathcal{N}_{\rm cr} + \mathcal{Q} = 0$$

$$\mathcal{Q} \propto \int_{E_{thr}}^{m_{DM}} dE_i \sum_f b_f \frac{dN_i^f}{dE_i}\left(\frac{\langle\sigma v\rangle}{m_{DM}^2}\right) \times \underbrace{\int \rho_{DM}^2(r)dV}$$

Particle physics   Astrophysics

Positrons :

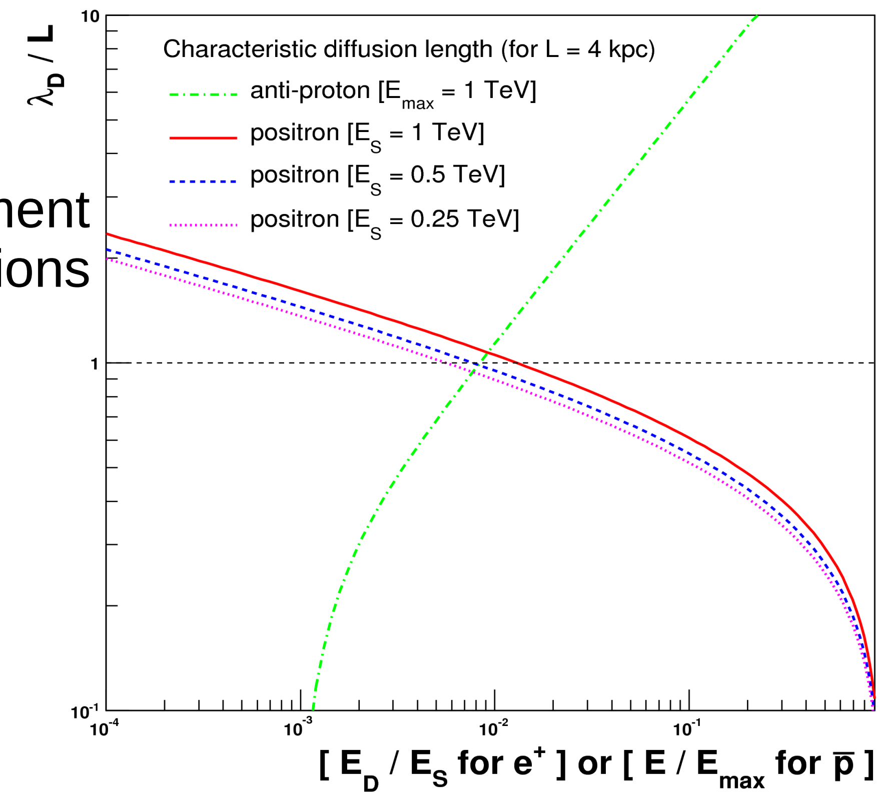
$$\lambda_D = \left\{\frac{4K_0\tau_E}{1-\delta}\left(\epsilon^{\delta-1} - \epsilon_S^{\delta-1}\right)\right\}^{1/2}$$

High / Low energies : come from local environment and depend on fluctuations

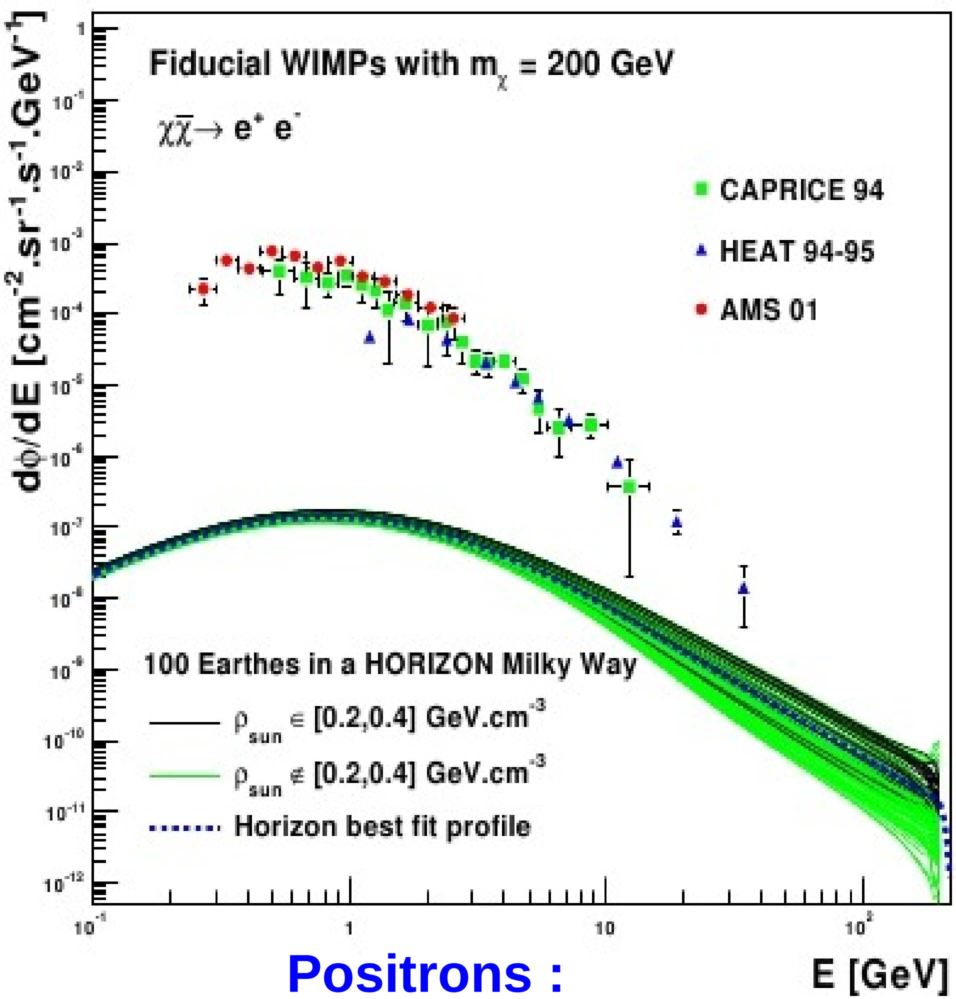
Low / High energies : large volume, smooth the fluctuations

Antiprotons :

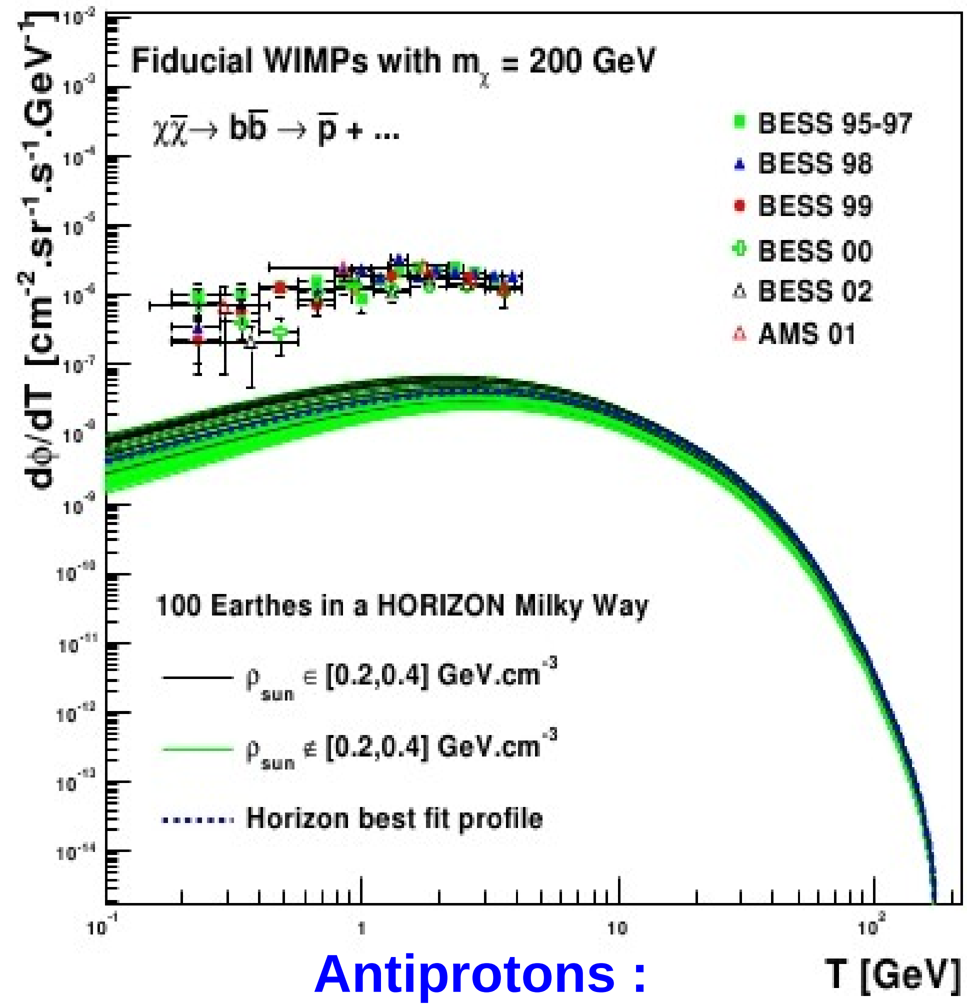
$$\Lambda_D = \frac{K(E)}{V_{\rm conv}}$$



Astrophysical uncertainties :



Positrons :



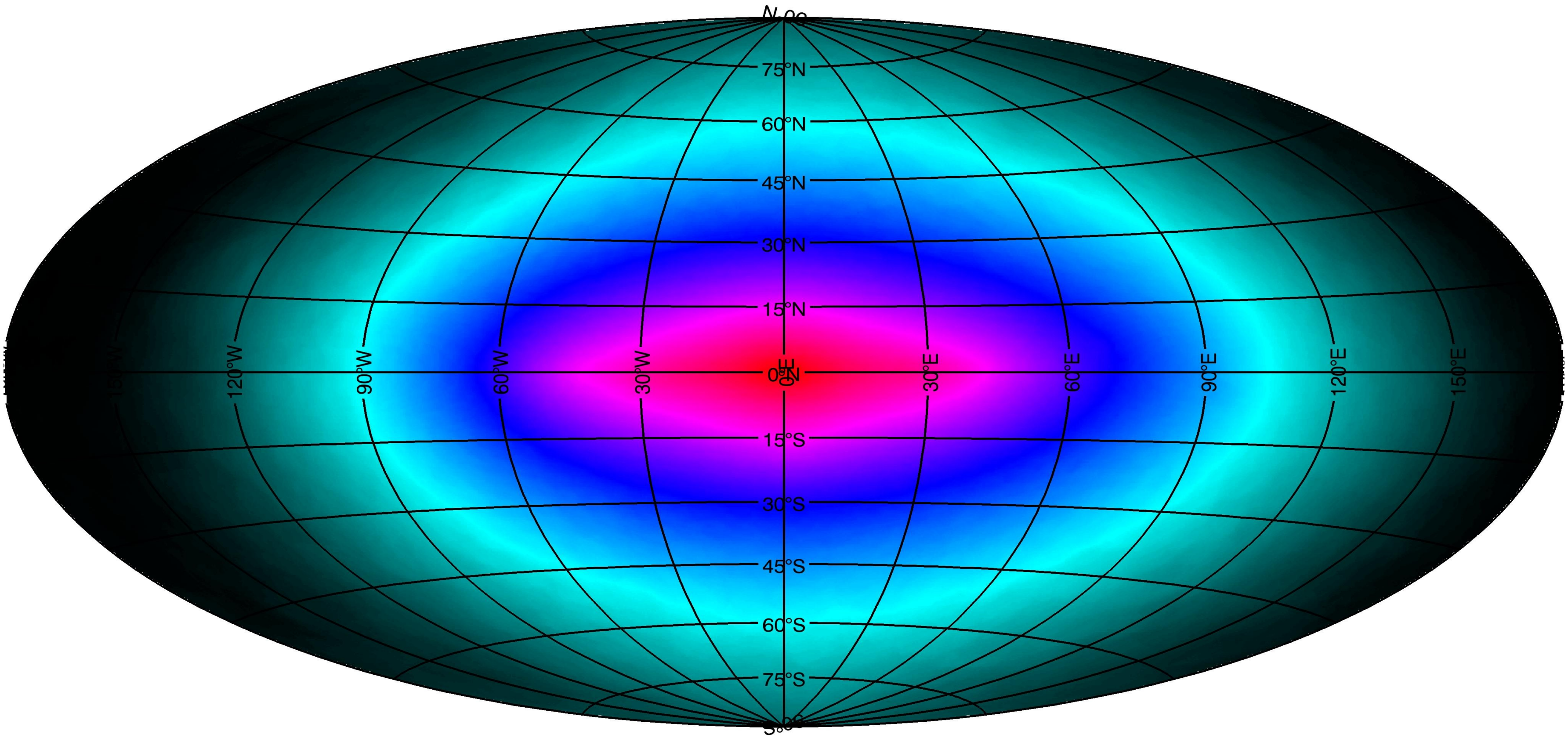
Antiprotons :

Cosmic rays in N-body framework :

Quantify the uncertainties related to local dark matter density

Use also the gas distribution to calculate signal and background (in progress)
Also use magnetic field distribution of simulations (future work)

Cosmic rays
N-body simulation : dark matter + baryons



star distribution → SNII explosion → cosmic rays distribution

Nezri, Lavalle, Teyssier … in progress

Summary-Conclusion

- **Cosmological N-body simulations with gaz : successful tool for galaxy formation**

- **Nb and dynamics of satellites**
- **Cusp/Core** (*Governato et al* arxiv:0911.2237)
- **Angular momentum problem**
  (bulges too dominant, discs not extended enough)
  (Agertz, Teyssier, Moore arxiv:1004.0005, Keres et al arxiv:1109.4638)

  → too concentrated objects

- **Improvement of ISM physics treatment**

- **Very consistent framework for dark matter detection and astroparticle calculations**
- **Dark matter signals (DD, γ, ν, CR)**
- **Backgrounds from gas, stars and ISM physics**

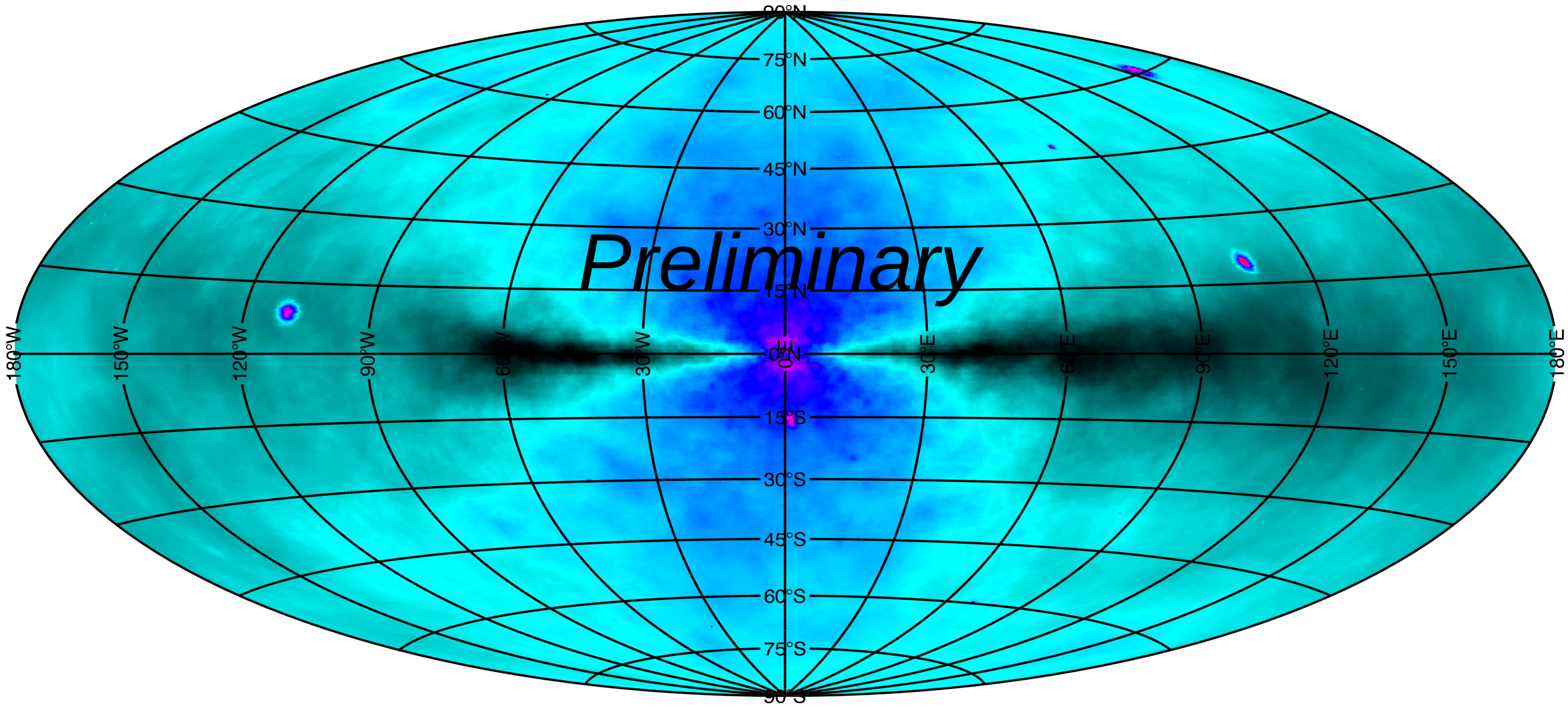
Nezri, Lavalle, Teyssier soon on arxiv... + future works
sarting a Ph D thesis : Pol Mollitor

Interface between N-body codes (Gadget, Ramses, Arepo ...)
and astroparticle codes (Micromegas, Darksusy, Galprop, Usine ...)

Thanks

Gamma skymap : DM versus π0 Background

N-body simulation : dark matter + baryons



Signal / background

Fermi bubbles ...

Nezri, Lavalle, Teyssier … soon on arxiv