

Dark matter indirect detection in cosmological N-body simulations

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Outline :

- **Introduction : N-body simulation basics**

Gamma Indirect detection of dark matter

- **signal**
- **background**

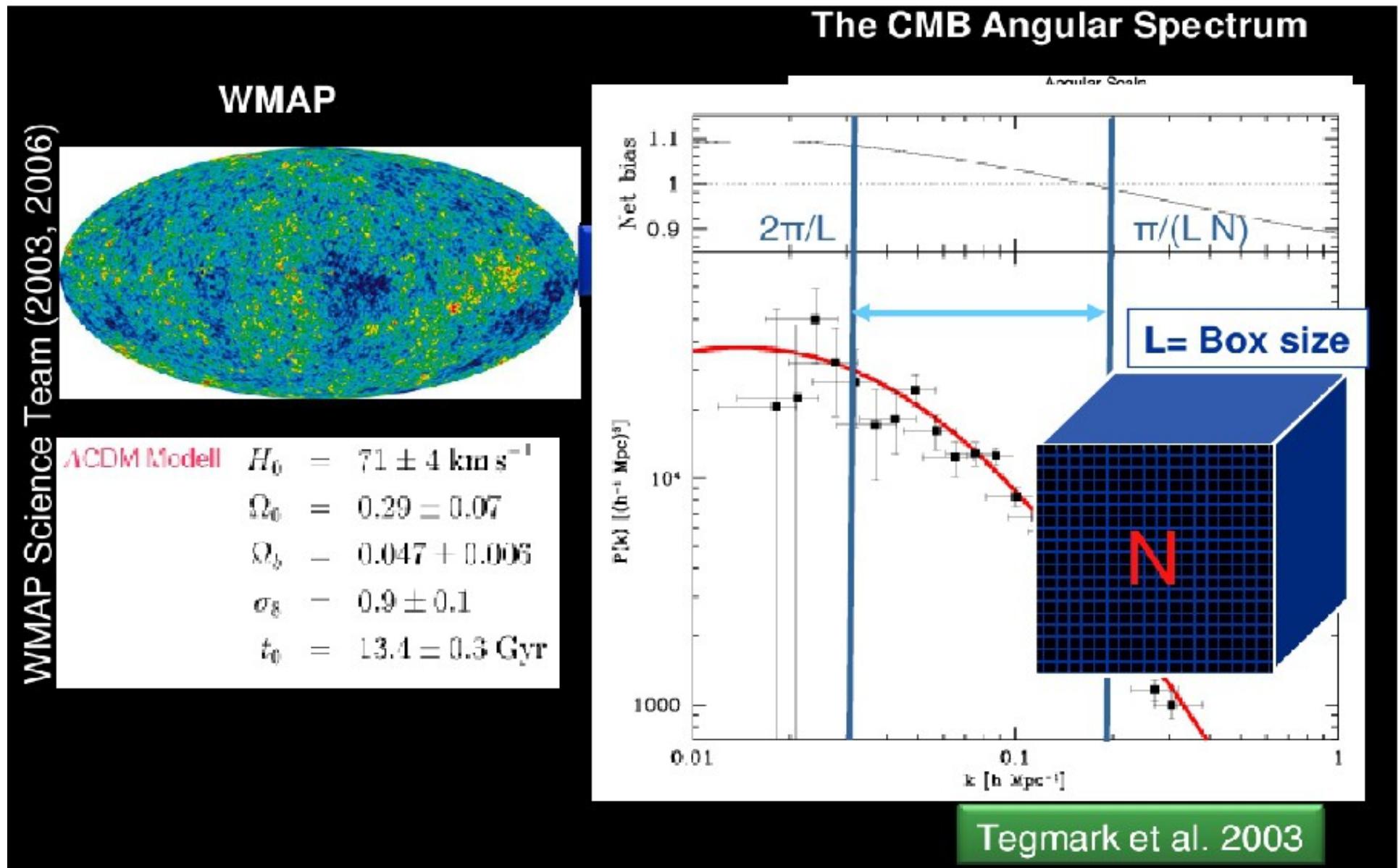
Introduction

Hierarchical structure formation scenario

- Cosmological 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

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

GAS

- Hydrodynamics : Euler equations
- + Gravity

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

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

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

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 :

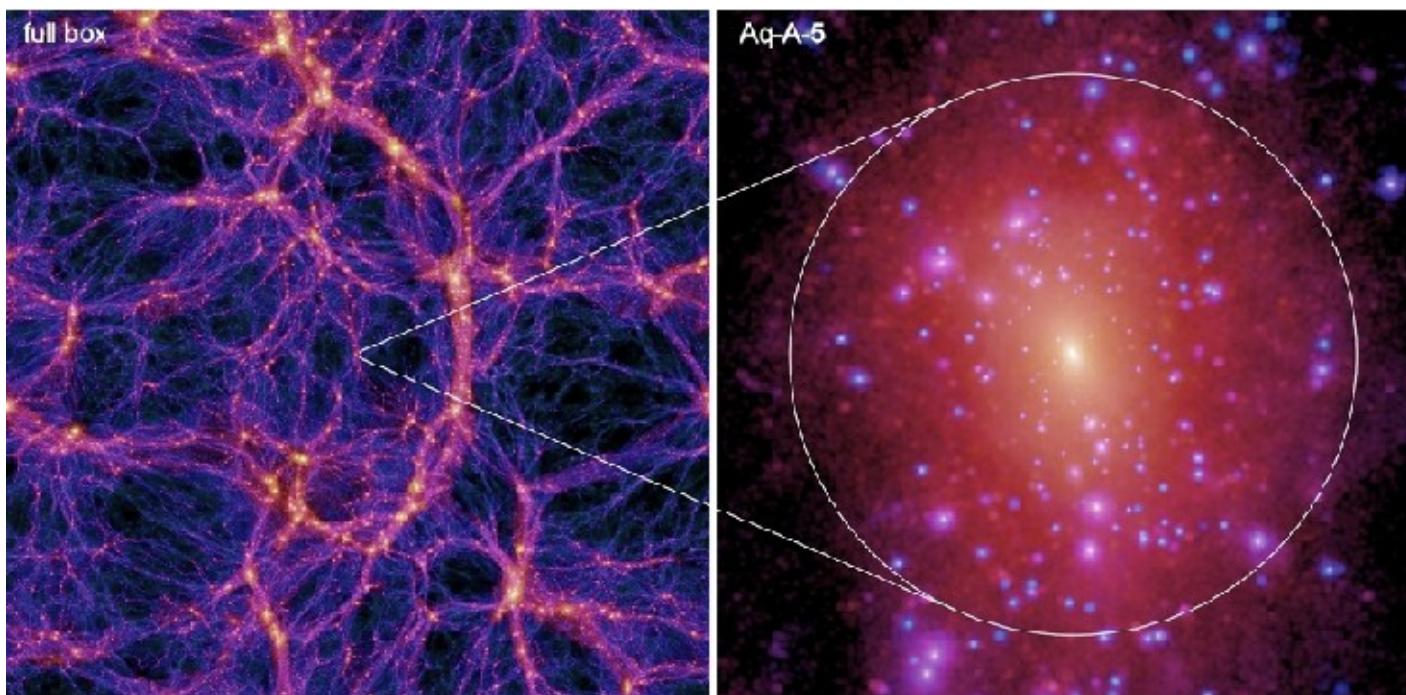
- Lagrangian : fluid=particles (SPH)
GADGET code (V.Springel)
- Eulerian : fluid=grid (AMR)
RAMSES code (R.Teyssier)
- “Hybrid”
AREPO (V.Springel)

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-Schechter, Sheth-Tormen)
= CLUMPS



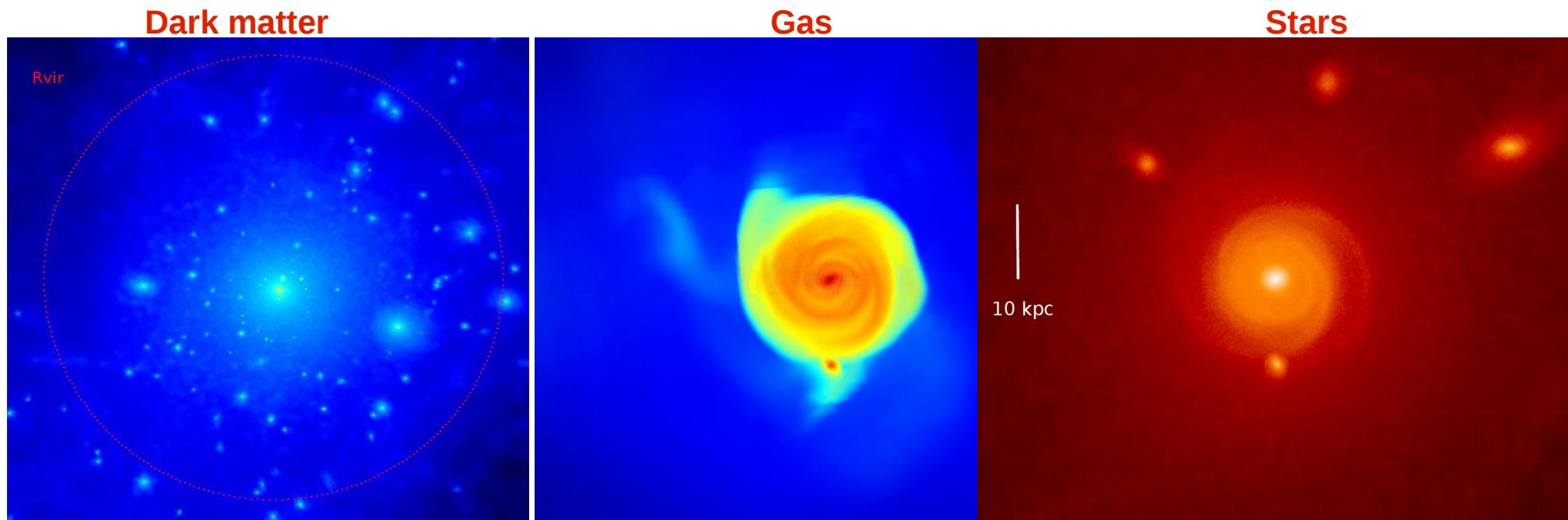
AQUARIUS, Springel et al 2008

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



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

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

- t_{ff} free-fall time
- ρ_0 threshold density
- ϵ_{ff} drive star formation rate

→ Transform gas into star particles

Supernovae feedback

- Type II SN, relevant for stellar masses $\sim 8-40 M_{\odot}$
- Represents $\sim 10\%$ of the mass of a stellar population
- Short lived stars
- $\sim 10\text{-}20$ Myr after the star (particle) creation : explosion
- $\sim 10\%$ of the star (particle) mass is re-injected into the gas
- Energy per explosion $E_{\text{SNII}} = 10^{51}$ erg
→ reheat the gas, can regulate star formation rate

Gamma Indirect detection

- Cosmological (and isolated) N-body + hydro simulations can provide realistic and very consistent MW like frameworks
- Signal = dark matter + particle physics
(can be also estimated with dark matter only simulations ... less consistency and information, better resolution)

Backgrounds : Cosmic ray interaction with ISM gas

Gamma/neutrino indirect detection

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

Particle physics **Astrophysics**

Annihilation cross section
Dark matter mass
Annihilation induced spectra

Any BSM extension
with WIMP candidate...

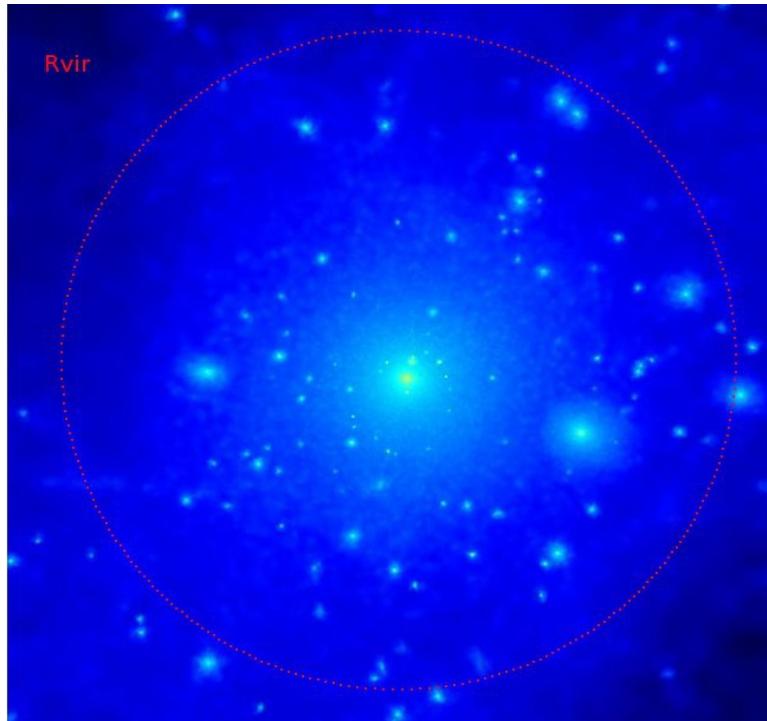
DM distribution:

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

Gamma/neutrino indirect detection

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

Particle physics **Astrophysics**



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Particle physics **Astrophysics**

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

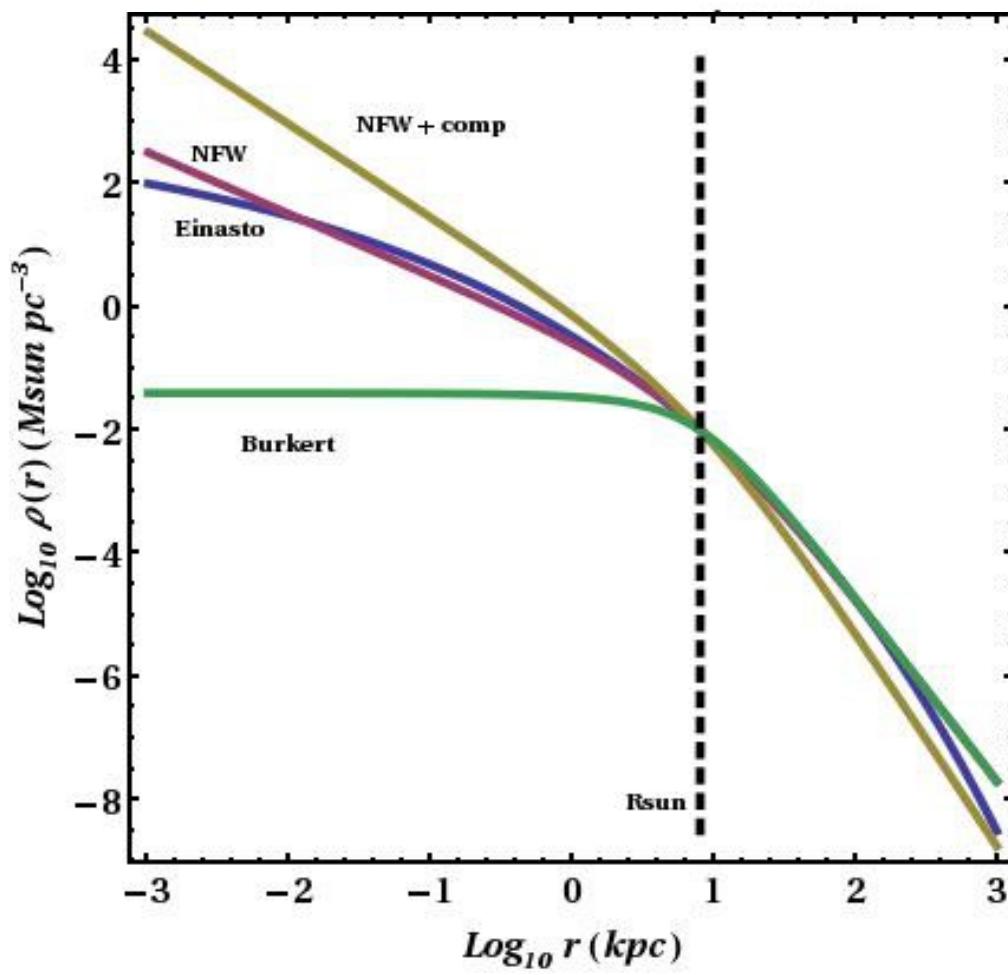
Spectrum $n \sim -1.8 - 2$
Calibration

DM distribution:

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

Gamma/neutrino indirect detection

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



DM distribution:

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Gamma/neutrino indirect detection

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

Particle physics **Astrophysics**

Approximation
Galactic Center, Fermi resolution :

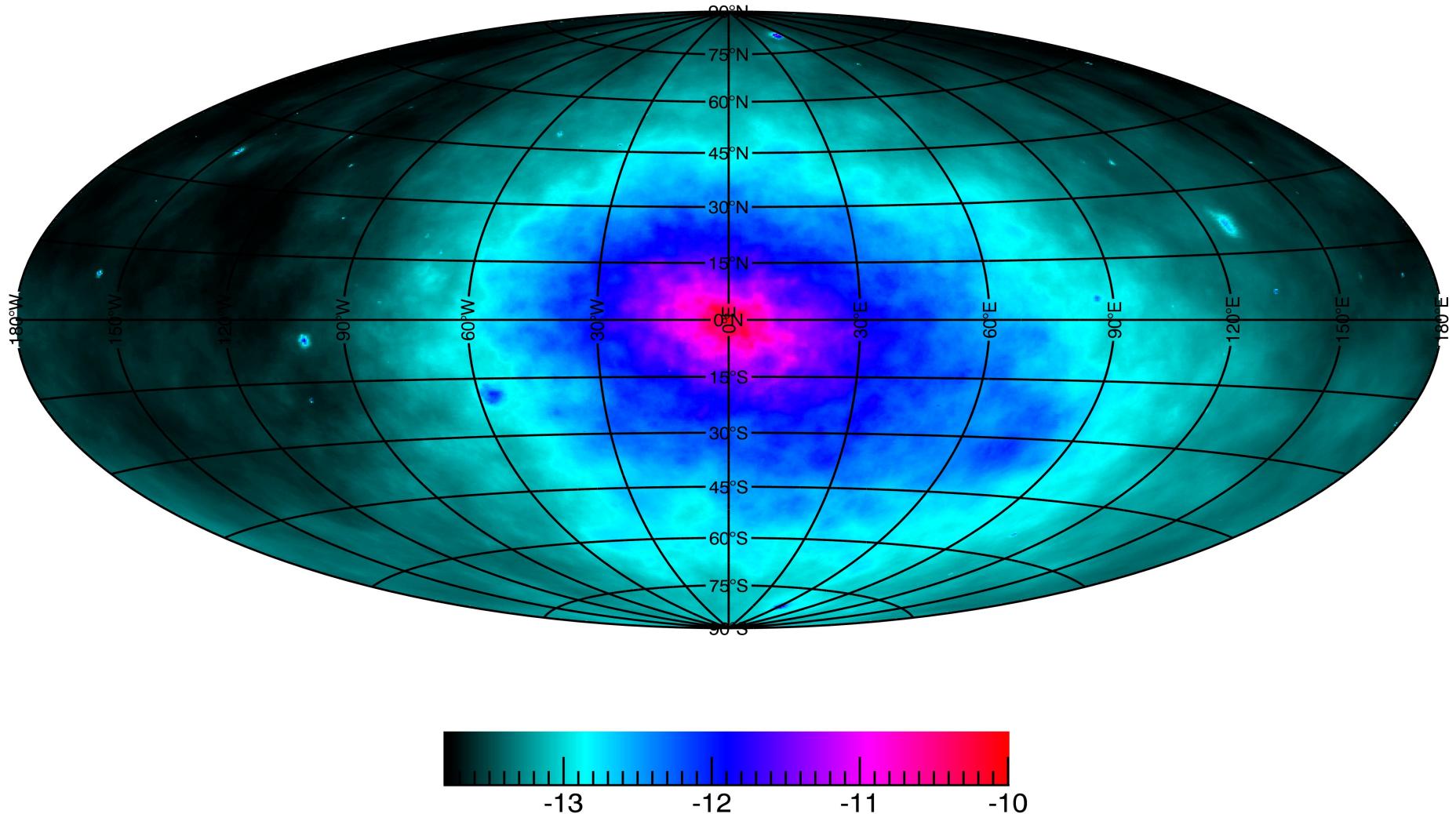
DM distribution:

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

$$\phi_{Einasto} \sim \phi_{NFW} \sim (100) \phi_{Core} \sim \frac{1}{(100)} \phi_{ad-comp}$$

Gamma/Neutrino skymap : Dark matter contribution

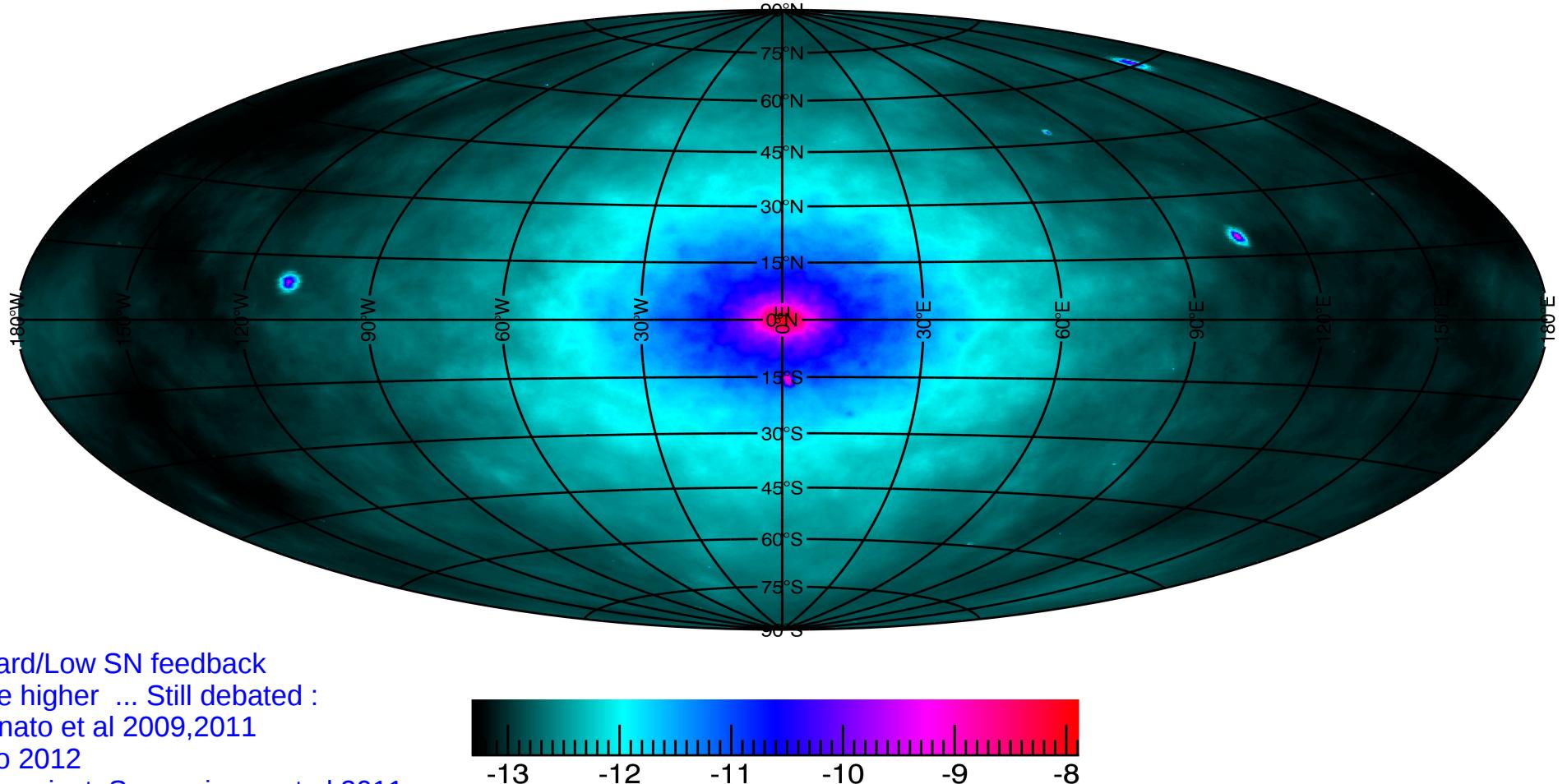
N-body simulation : dark matter only



+ standard thermal (HEP+cosmo) scenario
WIMP : $M_{DM} = 100 \text{ GeV}$, bbar, $\langle\sigma v\rangle = 3 \cdot 10^{-26} \text{ cm}^3/\text{s}$
Gammas : FERMI, HESS ~ -10

Gamma/Neutrino 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 ...

Diffuse Gamma emission

N-body simulation : dark matter + baryons

star distribution → SNII events → cosmic ray sources
Gas distribution → convolution with CR → gamma fluxes

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**Use SN feedback, star and gas distribution
to calculate diffuse hadronic gamma emission**

Diffuse Gamma emission

N-body simulation : dark matter + baryons

star distribution → SNII events → cosmic ray sources
Gas distribution → convolution with CR → gamma fluxes

arxiv:1204.4121 Nezri, Lavalle, Teyssier

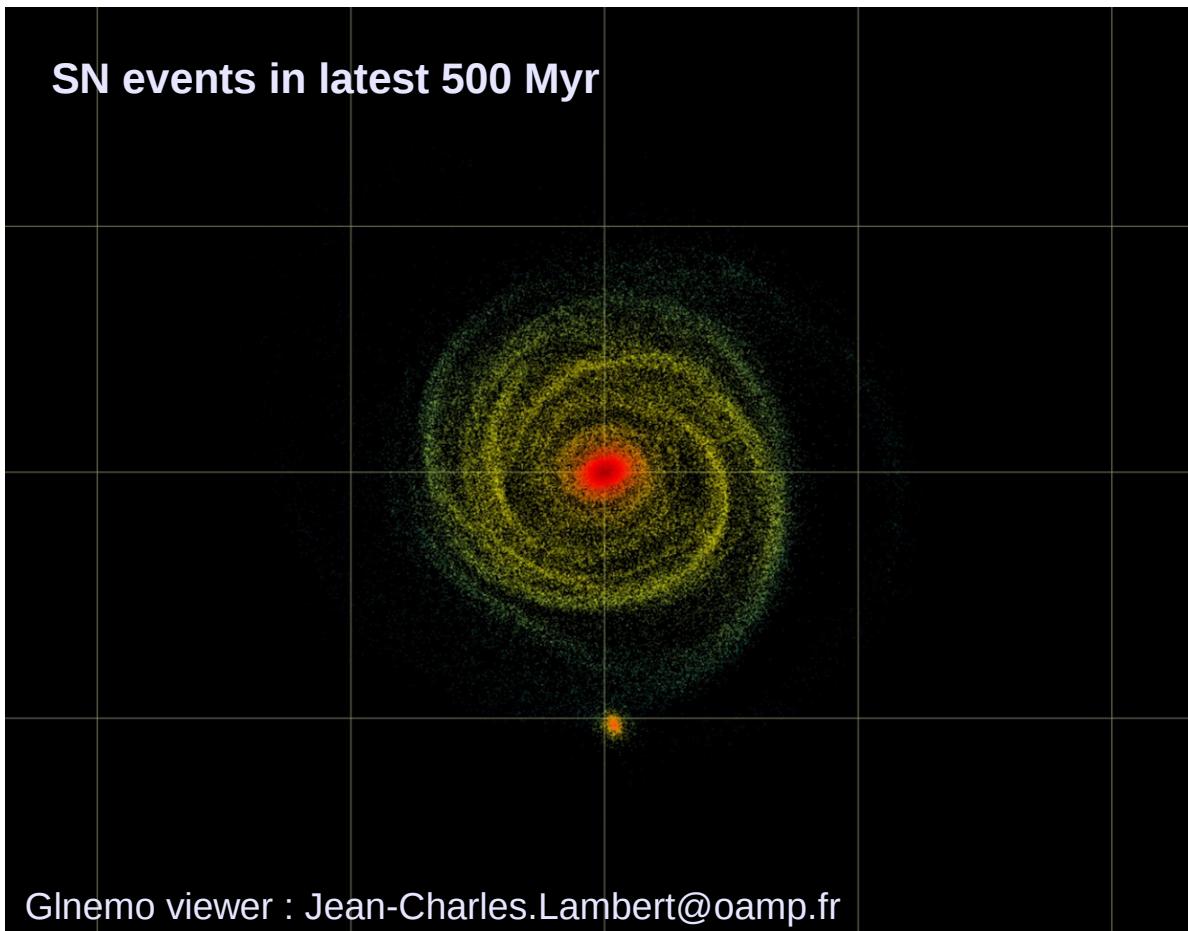
- Star distribution
- IMF 10% -> massive stars
- Age= 20 Myr -> Type II SN
- Energy per explosion $E_{\text{SNII}} = 10^{51} \text{ erg}$
- 10 % used as feedback energy
- 10% converted into high energy cosmic rays with a power law energy spectra : E^{-2}
- Select all SN events in the latest 500 Myr ~ 85 000 particles (typical residence time of Crs in the Galaxy)
- Explosion rate ~ 3/100 yr

Diffuse Gamma emission

N-body simulation : dark matter + baryons

star distribution → SNII events → cosmic ray sources
Gas distribution → convolution with CR → gamma fluxes

arxiv:1204.4121 Nezri, Lavalle, Teyssier



**Gamma emission : π^0 Background
N-body simulation : dark matter + baryons**

star distribution → SNII events → cosmic ray sources

Gas distribution → convolution with CR after propagation → gamma fluxes

arxiv:1204.4121 Nezri, Lavalle, Teyssier

Cosmic ray propagation :

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

Consider protons and Helium

Hadronic part of the diffuse gamma-ray emission above few GeV

Spatial diffusion essentially

Diffusion coefficient : $K(\mathcal{R}) \equiv |p|/q = 0.01 \text{ kpc}^2/\text{Myr} (\mathcal{R}/1 \text{ GV})^{0.7}$

-> full CR distribution

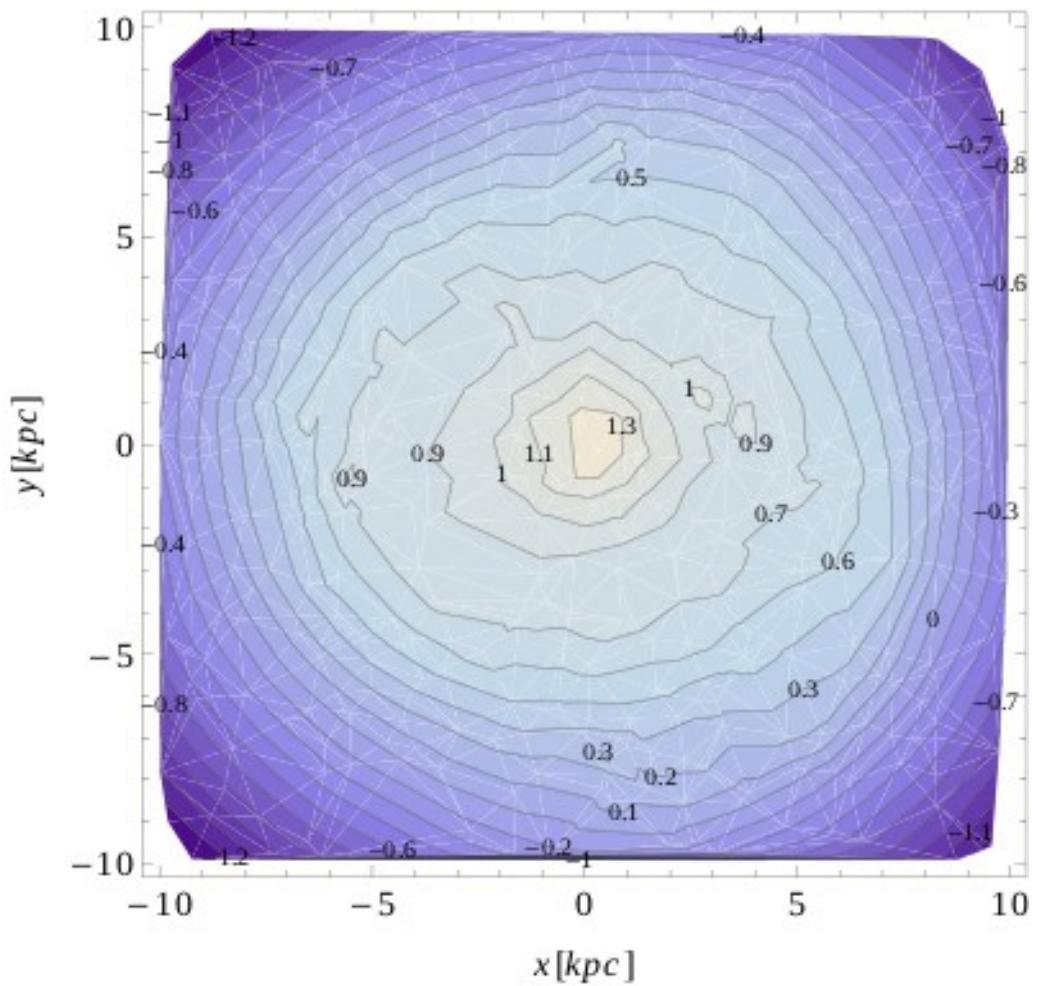
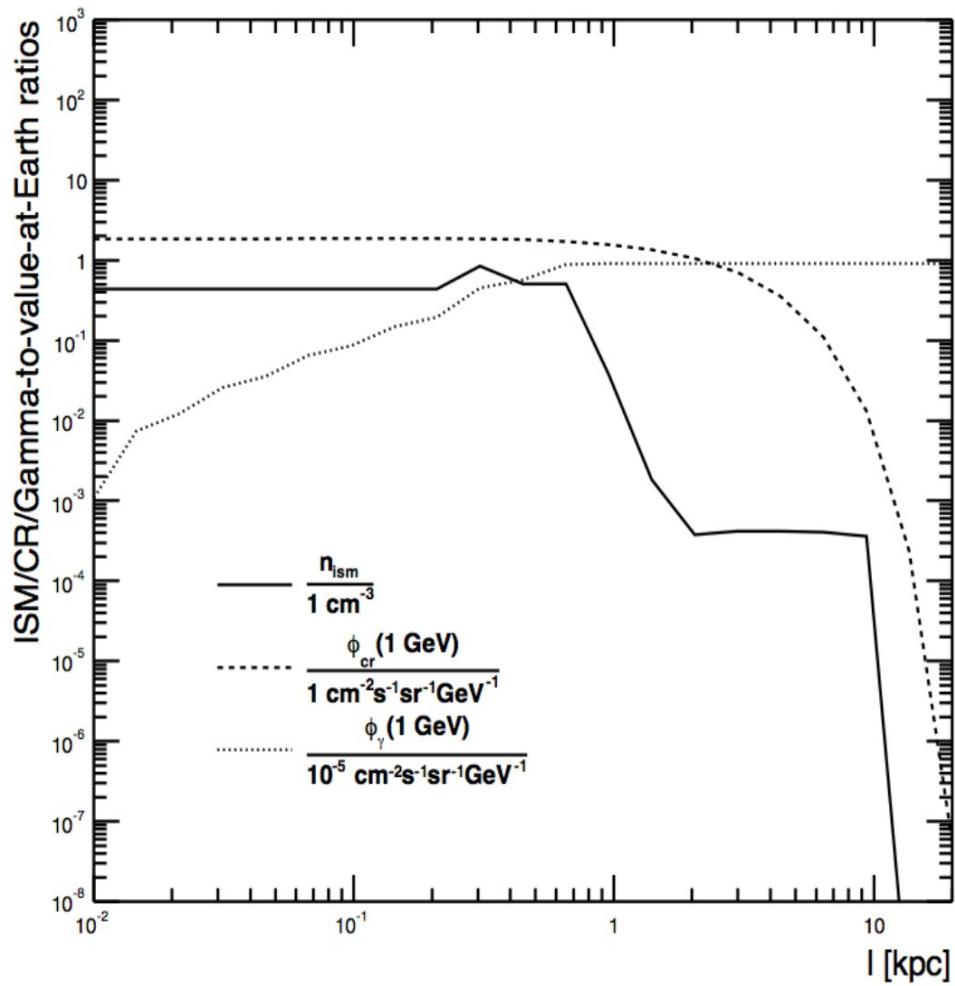
Diffuse Gamma emission

N-body simulation : dark matter + baryons

star distribution → SNII events → cosmic ray sources → propagation

Gas distribution → convolution with CR → gamma fluxes

arxiv:1204.4121 Nezri, Lavalle, Teyssier



Diffuse Gamma emission

N-body simulation : dark matter + baryons

star distribution → SNII events → cosmic ray sources → propagation

Gas distribution → convolution with CR → gamma fluxes

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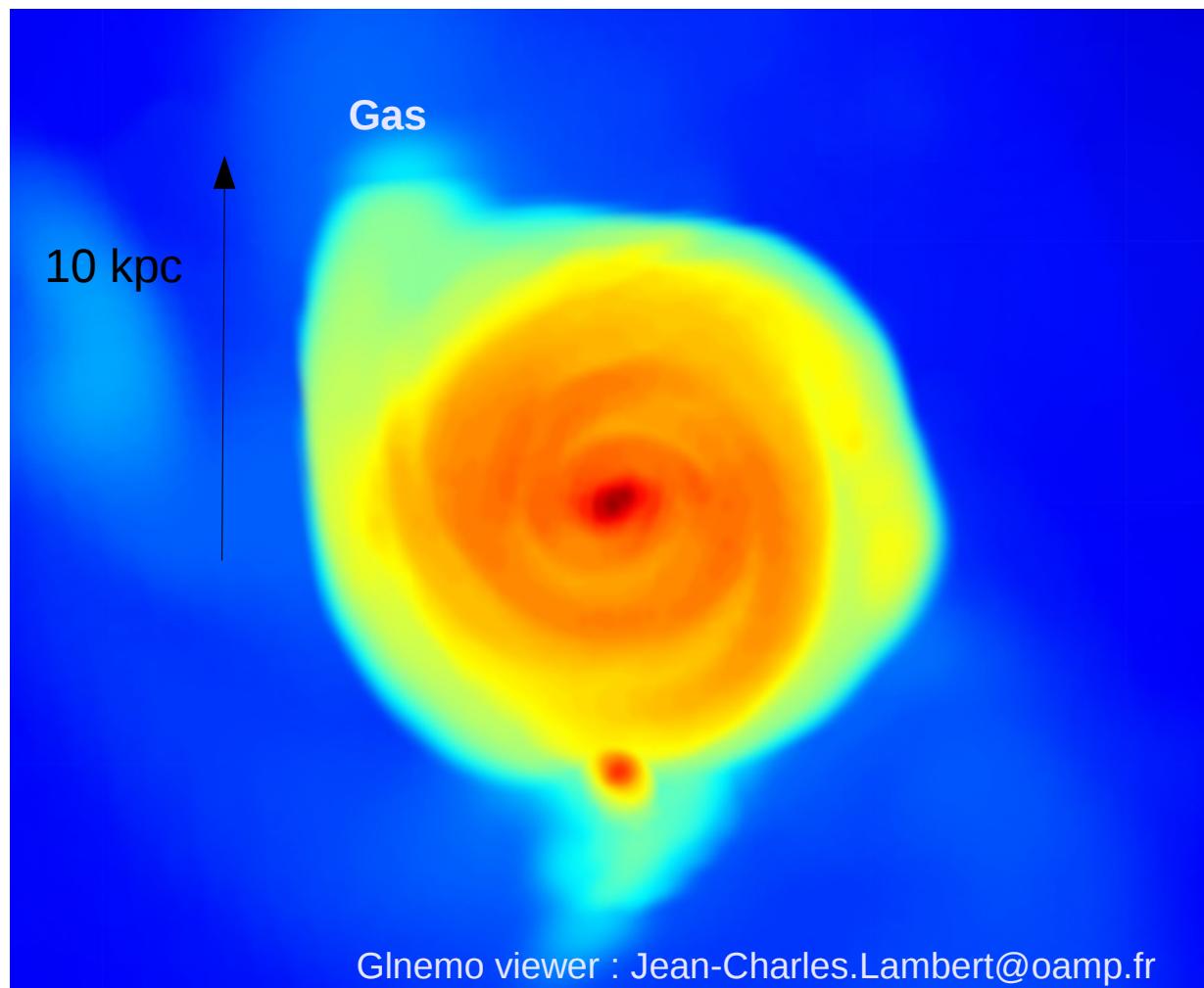
Diffuse Gamma emission

N-body simulation : dark matter + baryons

star distribution → SNII events → cosmic ray sources → propagation

Gas distribution → convolution with CR → gamma fluxes

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Angular momentum problem
Disk, small, thick

Depends on SF, SN feedback ...

Diffuse Gamma emission

N-body simulation : dark matter + baryons

star distribution → SNII events → cosmic ray sources → propagation

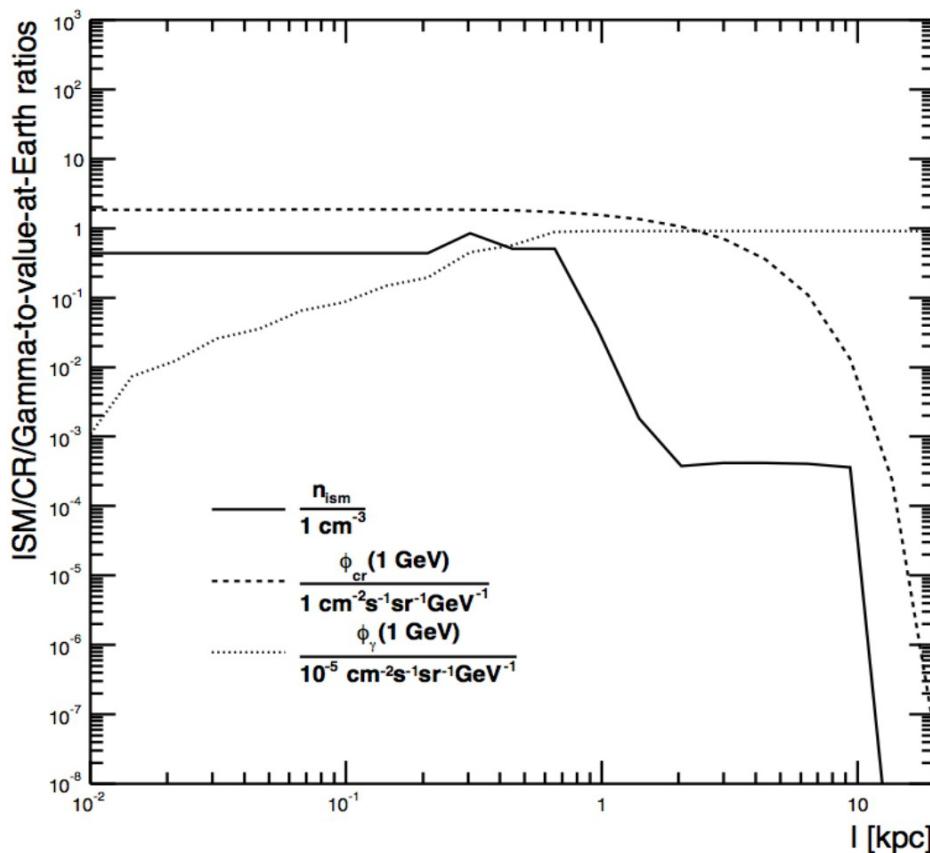
Gas distribution → convolution with CR → gamma fluxes

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- Relative amount

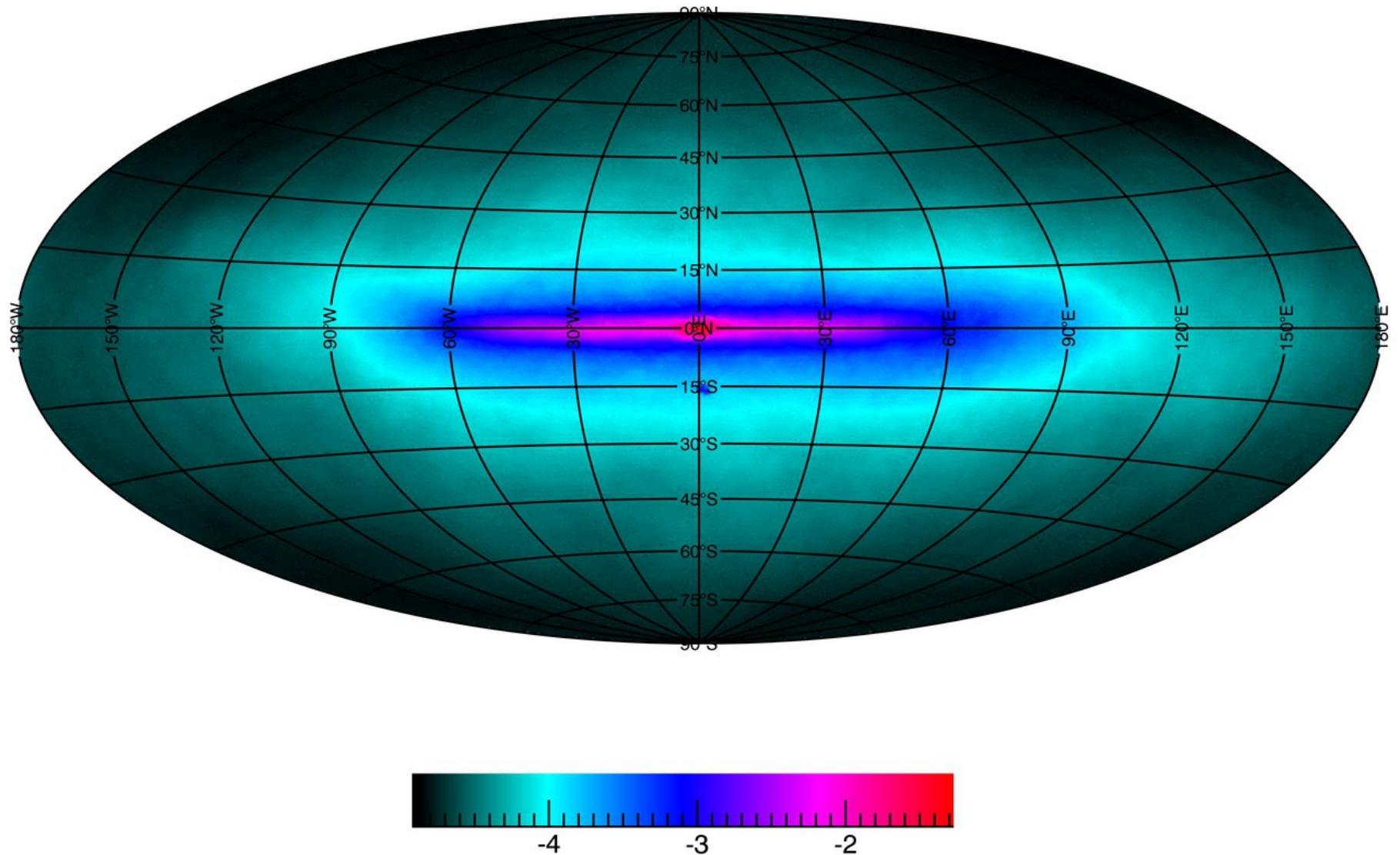
Hydrogen:Helium 9:1

- Hadronic cross sections parametrisation Kamae et al 2006



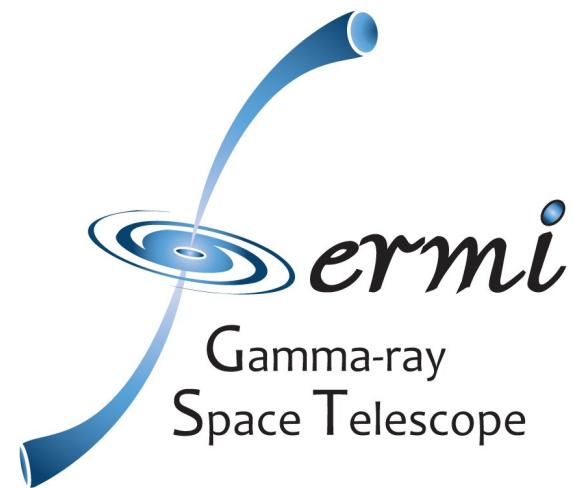
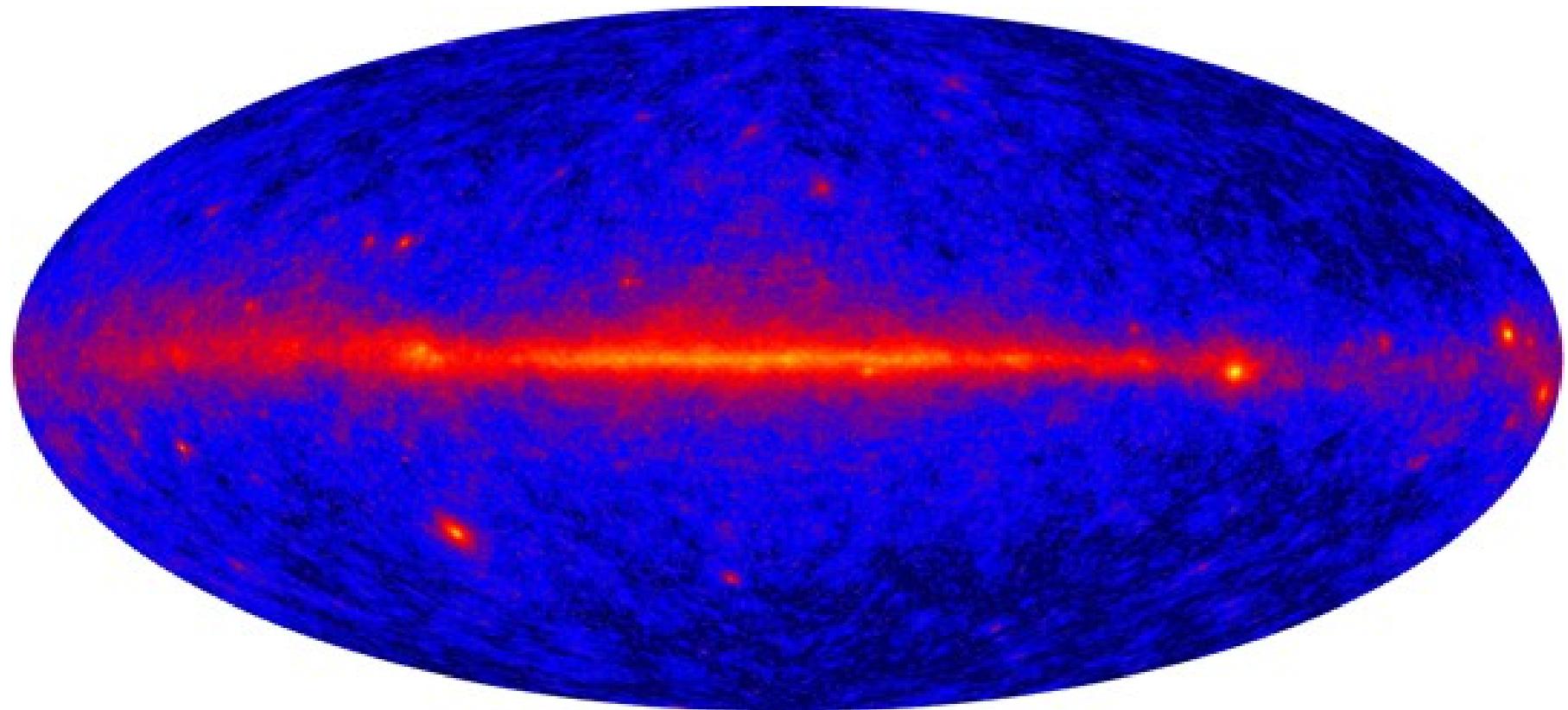
Diffuse Gamma emission

N-body simulation : dark matter + baryons



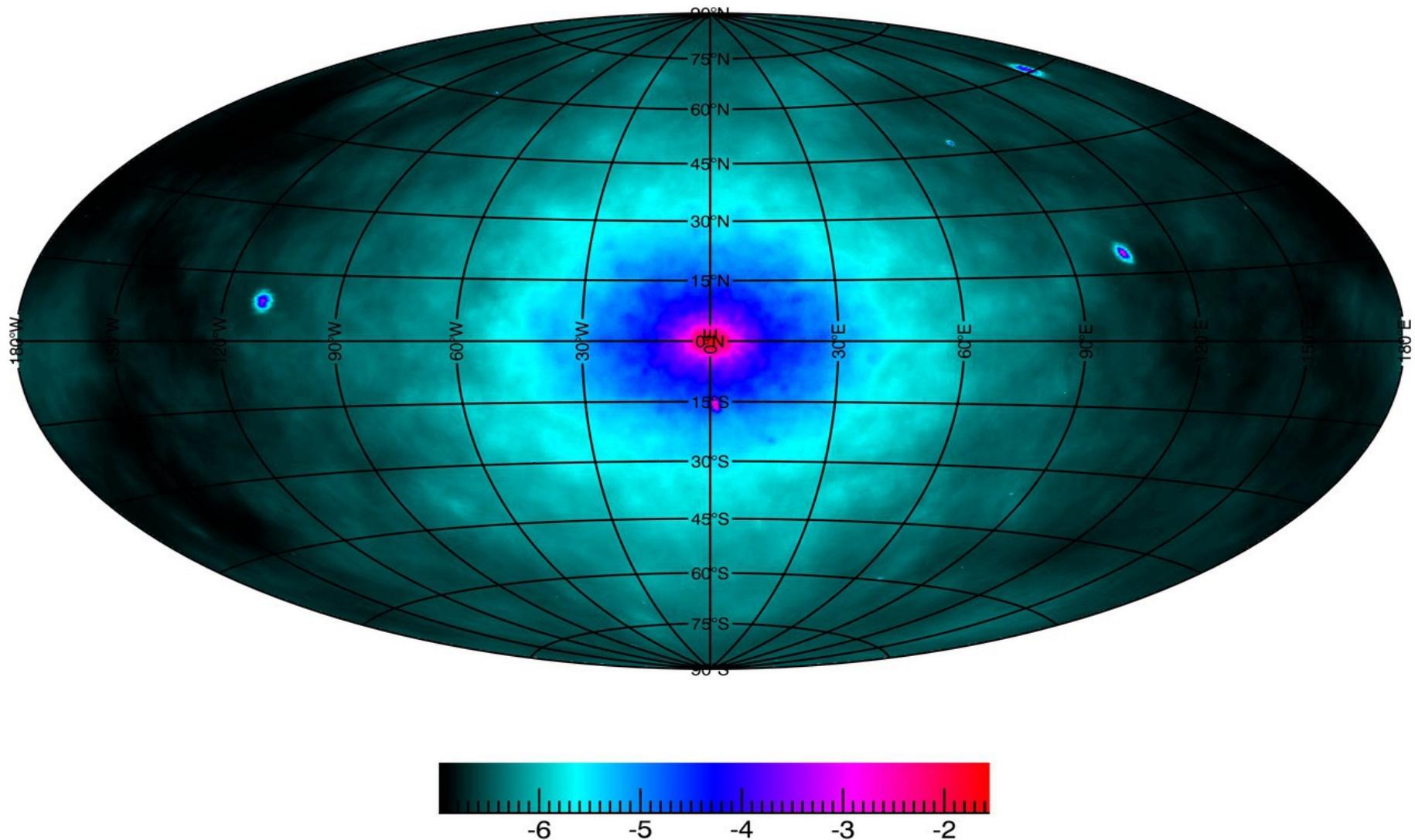
Comparable with Fermi ... (disc morphology)

arxiv:1204.4121 Nezri, Lavalle, Teyssier



Dark matter annihilation

N-body simulation : dark matter + baryons

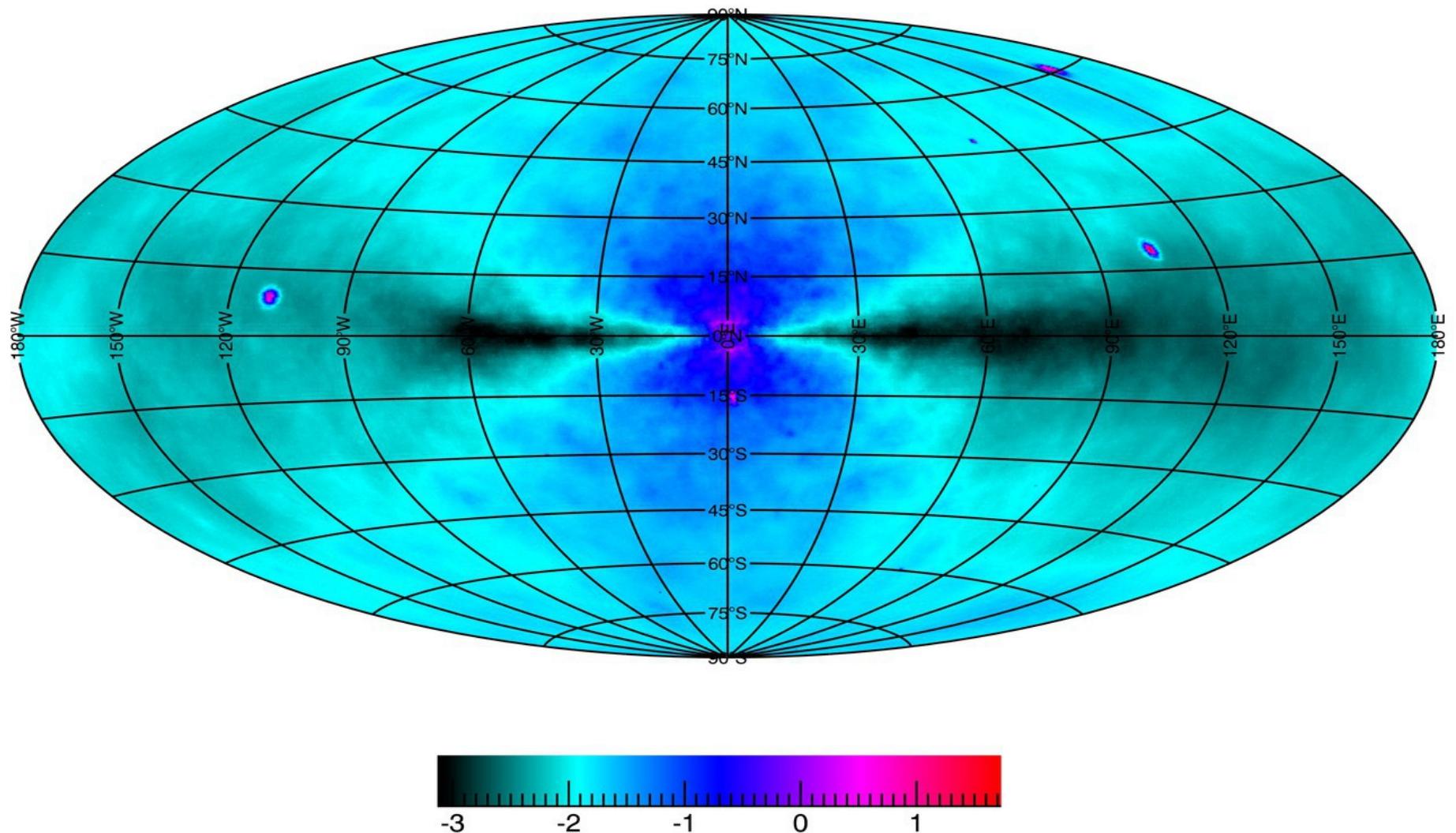


WIMP : $M_{DM} = 100 \text{ GeV}$, $b\bar{b}$, $\langle \sigma v \rangle = 3 \cdot 10^{-26} \text{ cm}^3/\text{s}$

Could be increased with lighter WIMP (Signal $\propto 1 / M^2$)

Signal/Background ratio

N-body simulation : dark matter + baryons



Adiabatic compression enhance also background
(large gas density at the very center, high local star formation
large local SN explosion rate and CR density)

-> not so optimistic for dark matter detection

arxiv:1204.4121 Nezri, Lavalle, Teyssier

Conclusion

Summary :

- **Cosmological N-body + hydro simulations :**
very consistent frameworks for dark matter detection
and cosmic-ray calculations

-> Signals AND backgrounds

ASTRO – HEP interplay :

- can give the most consistent
and realistic predictions for astroparticles
- New powerful diagnostic tool to test simulations from high energy

Perspectives : improved treatment of baryons (star formation, feedbacks ...)

- Can/will be applied to neutrinos and cosmic-rays
-> Multi wavelength and multi messenger studies
- MHD simulations : magnetic field distribution from the simulation ... in progress
- Isolated simulations (disk, bar, spiral arms) especially for diffuse emissions
- Cluster scale simulation (more backgrounds ...)

Thanks

Local dark matter

Capture rate :

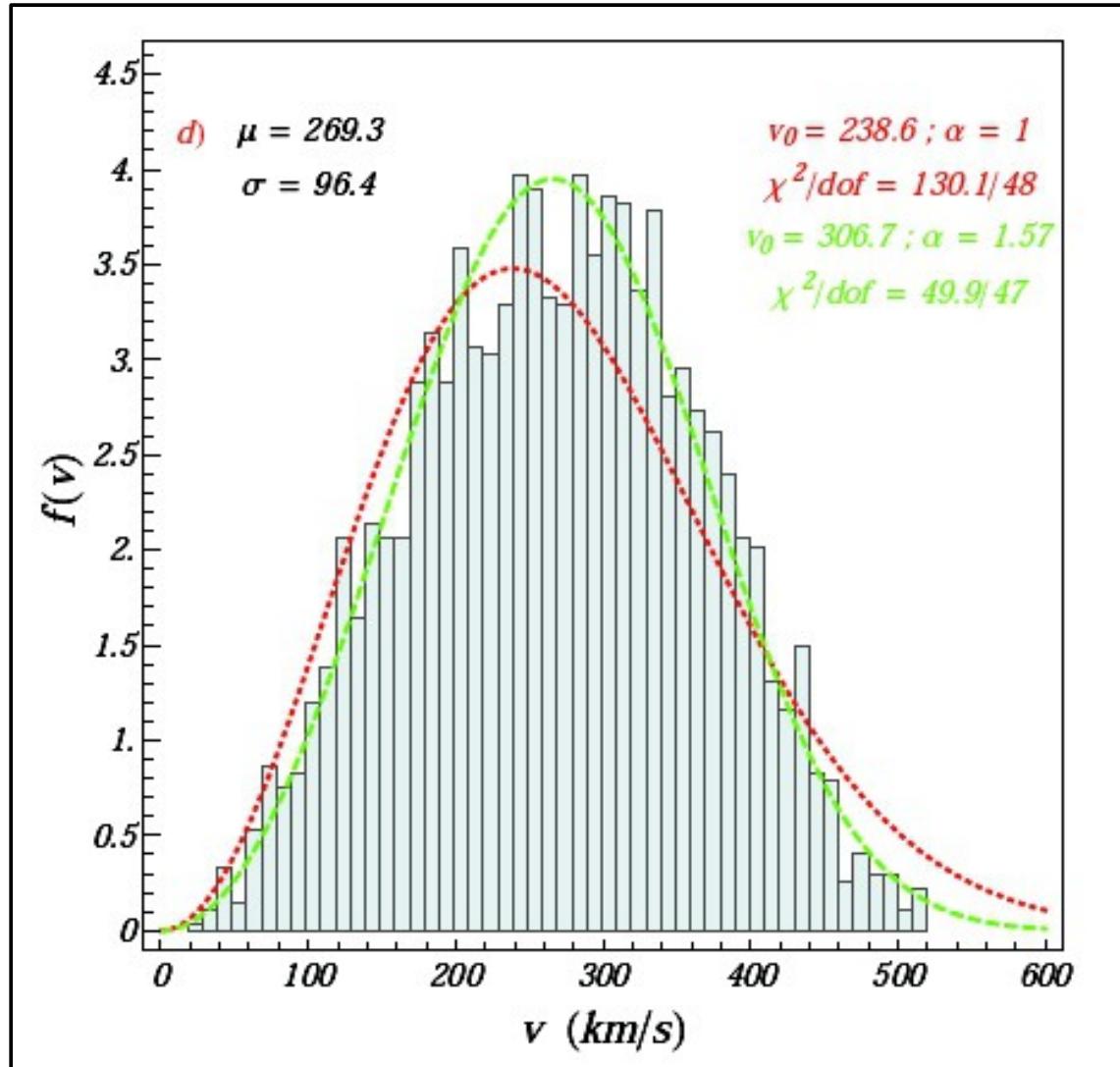
- Local dark matter density
- Velocity distribution

Features \neq Maxwellian ?
Dark disk ?
Corotation ?

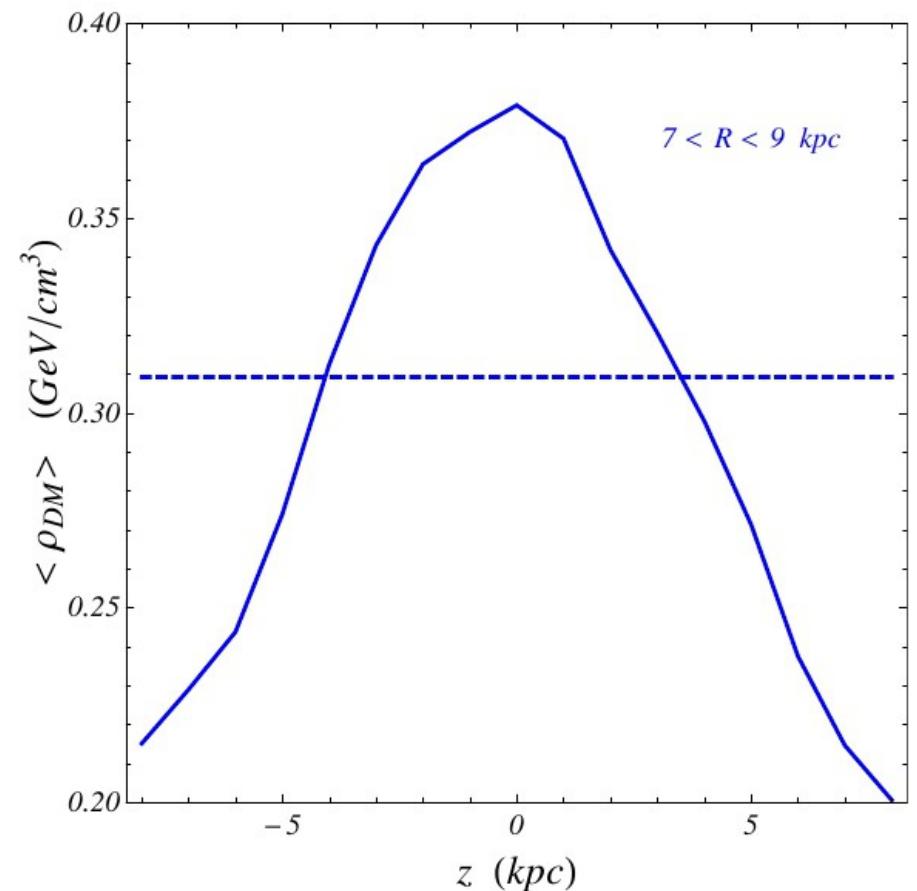
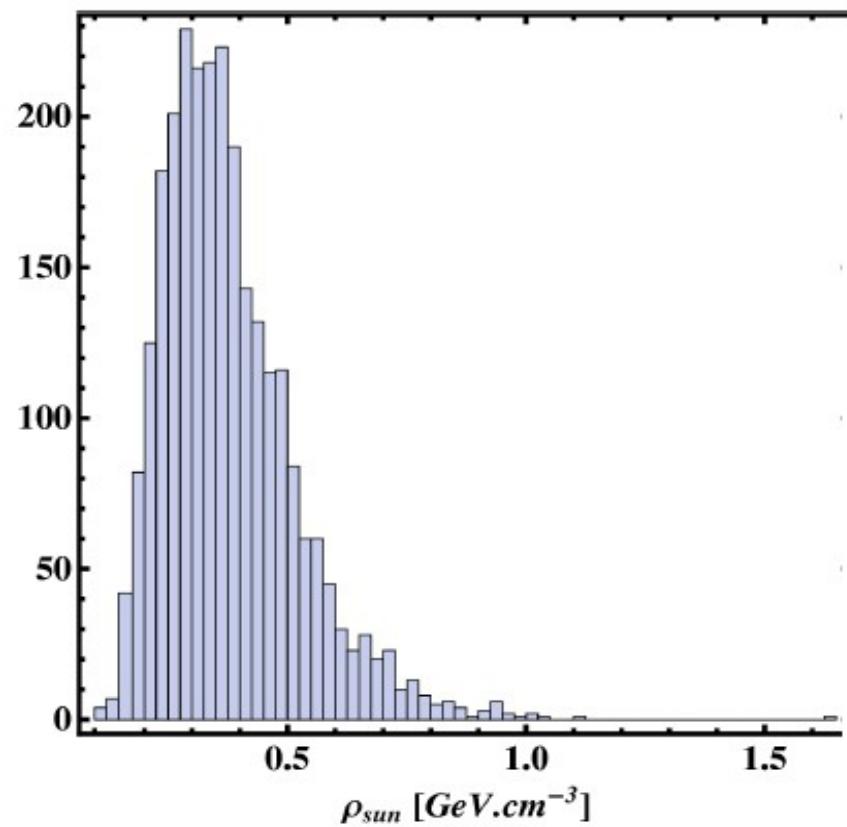
$$\eta = \int d^3\vec{v} \frac{f(\vec{v})}{|\vec{v} - \vec{v}_{\oplus,G}|}$$

Dark disc : clump accretion by stellar and star disc ... *Read et al 0902.0009*
→ enhancement of DD and neutrino telescope signal ?
capture rates in the Sun ? *Bruch et al 2009 vs Ling 2010*

Simulation : Dark matter velocity distribution



Cosmological simulation : Local DM density, Dark disk ?



$$\text{Mean}(\rho_{\text{sun}}) > 0.3 \text{ GeV.cm}^3$$

Cosmic rays

collaboration with J. Lavalle

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

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

Positrons :

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

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

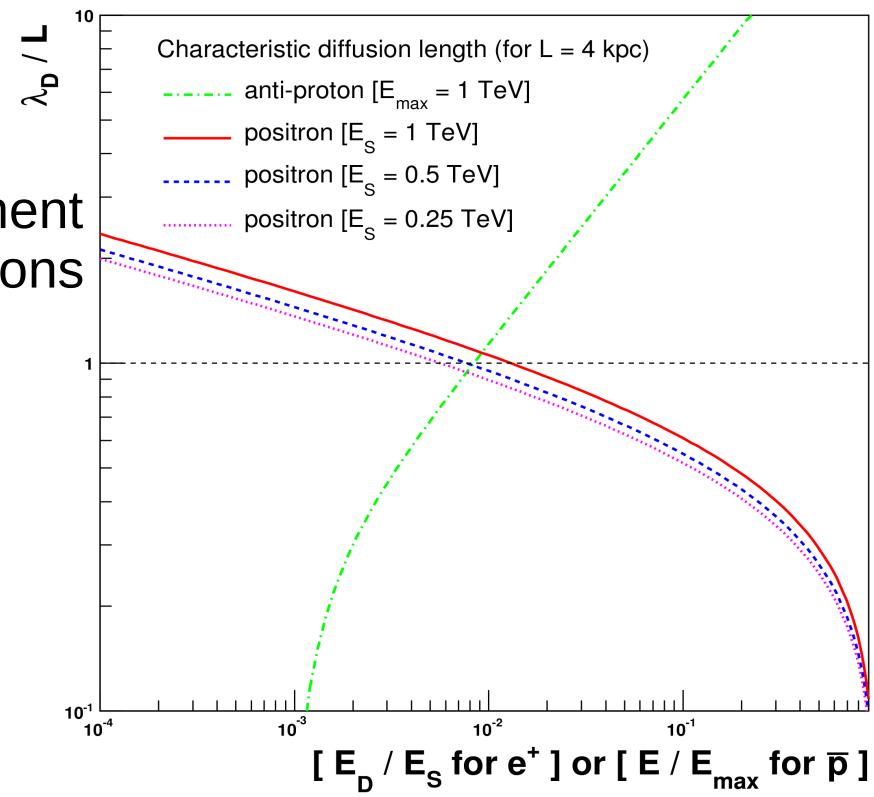
Low / High energies : large volume,
smooth the fluctuations

Antiprotons :

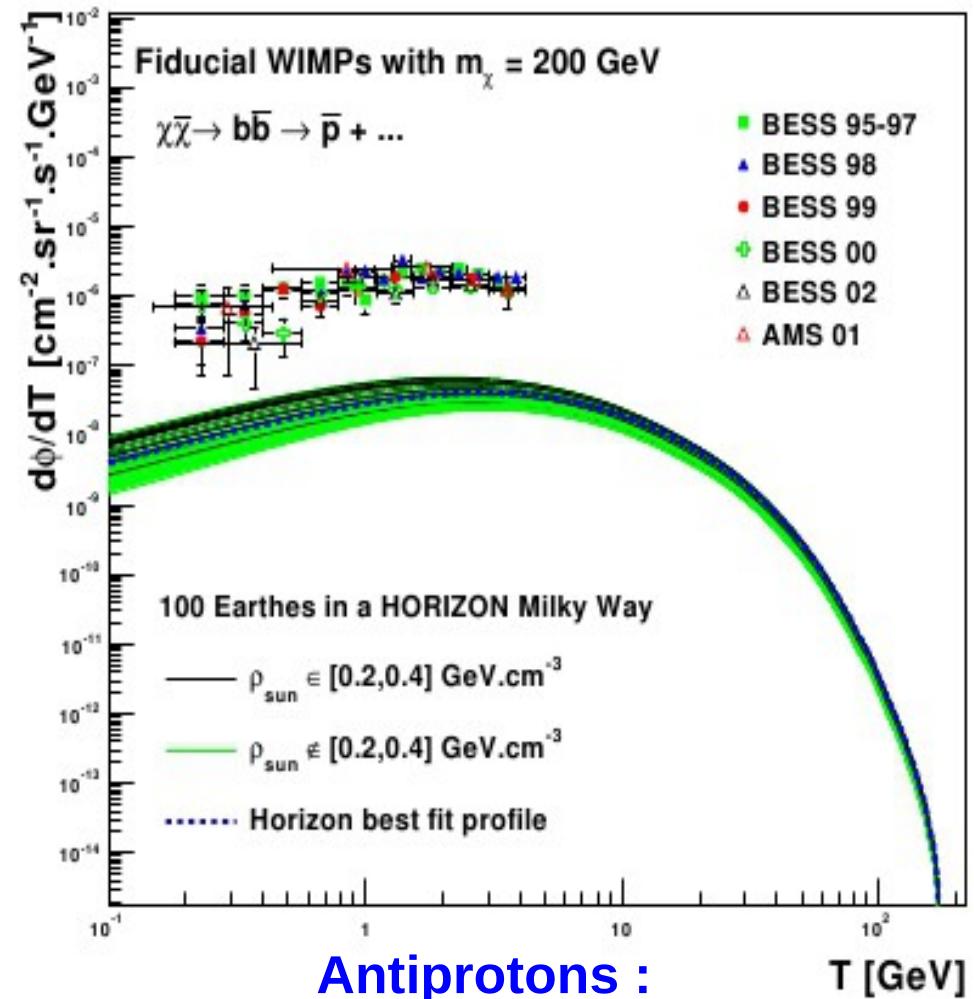
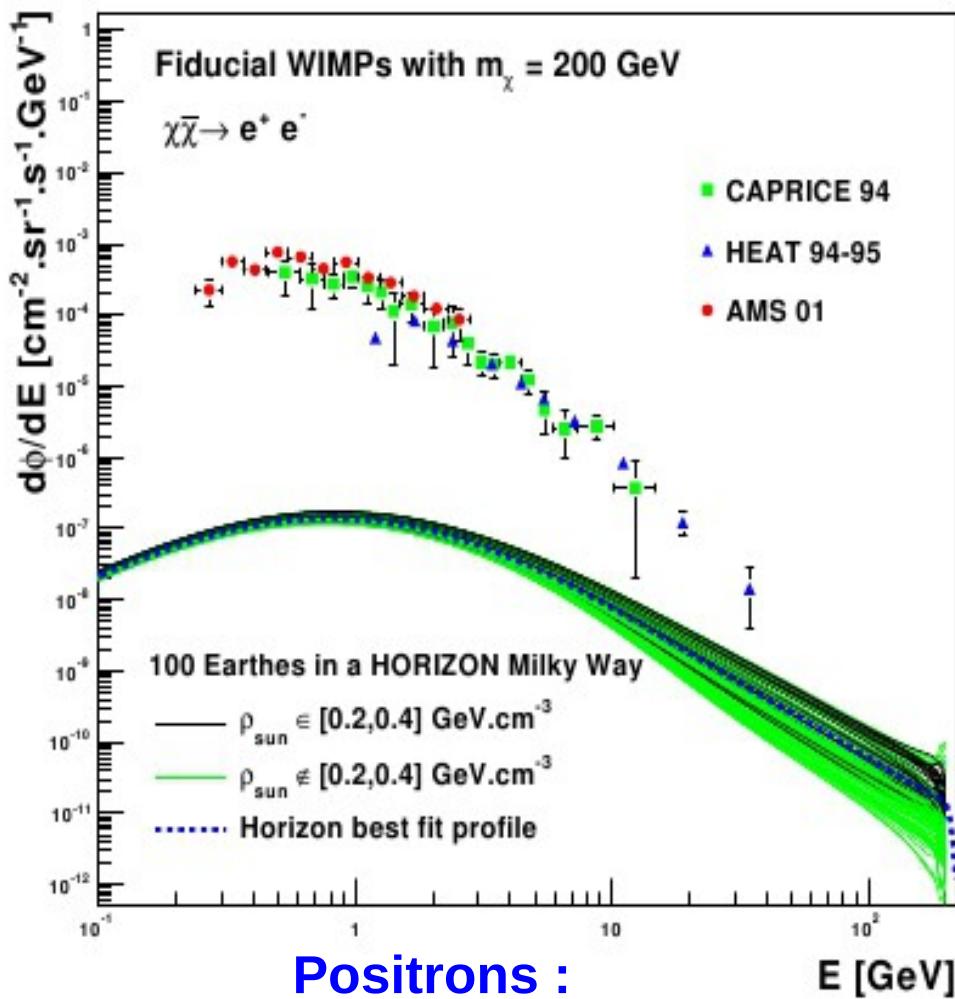
$$\Lambda_D = \frac{K(E)}{V_{\text{conv}}}$$

Particle physics

Astrophysics



Astrophysical uncertainties :



Cosmic rays in N-body framework :

Quantify the uncertainties related to local dark matter density

arxiv:0808.0332 Lavalle, Nezri, Ling, Athanassoula, Teyssier

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

(Cuspy ?) Dark matter Halos

Fit of N-body results :

- Cusps

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

- Einasto (AQUARIUS)

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

- Burkert :

$$\rho(r) = \frac{\rho_0 r_0}{(r+r_0)(r^2+r_0^2)}$$

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

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
- Stellar formation rate could help to solve angular momentum problem
(=bulges too dominant, discs not extended enough)
-> more realistic (larger) disk. *Agertz, Teyssier, Moore* arxiv:1004.0005
- Higher feedback could erase the cusp even in massive spirals. *Maccio et al* arxiv:1111.5620

Still debated ...