Mapping dark matter structures through gamma-rays

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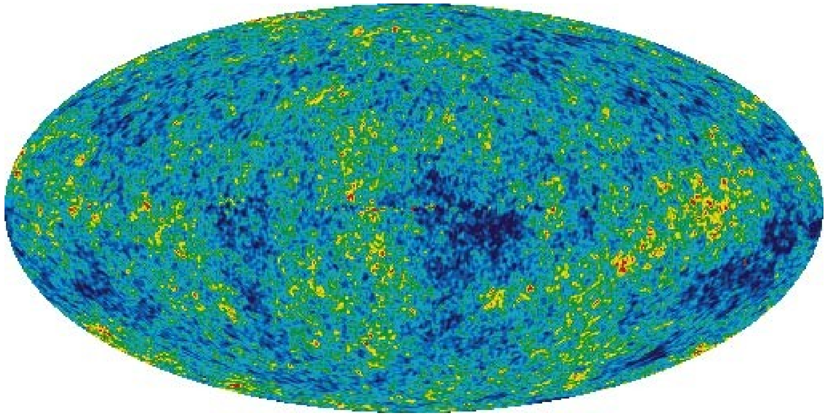
Outline

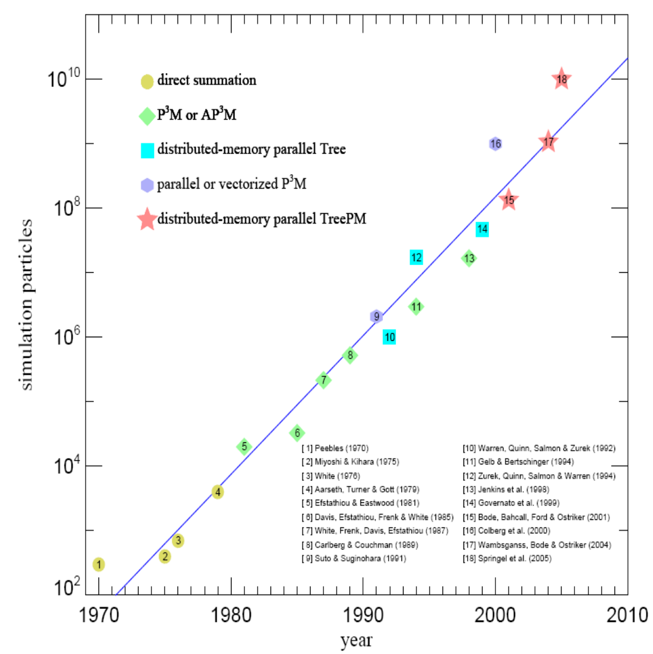
- Numerical simulations of structure formation.
- Gamma-ray spectrum from annihilation of neutralinos.
- Gamma-ray emission from dark matter halos.
- Specific intensity and the EGB radiation from annihilation.

Numerical simulations of structure formation

- In the ΛCDM model the structures that we see today evolved from the primordial density perturbations imprinted in the CMB.
- Gravity drives the evolution and the perturbations grow hierarchically to eventually form dark matter haloes where galaxy formation happens.
- Initial conditions are given by the parameters of the LCDM model (Ω_{DM}, Ω_{Λ}, h, etc.) which are directly probed by observations such as the CMB.
- Linear perturbation theory works as long as $\delta\rho/\rho_0 << 1$
- N-body simulations for the non-linear regime
- Density field - > Discret set of particles
- Large number of particles (expensive!!)
- Improvements on the computational power and algorithms



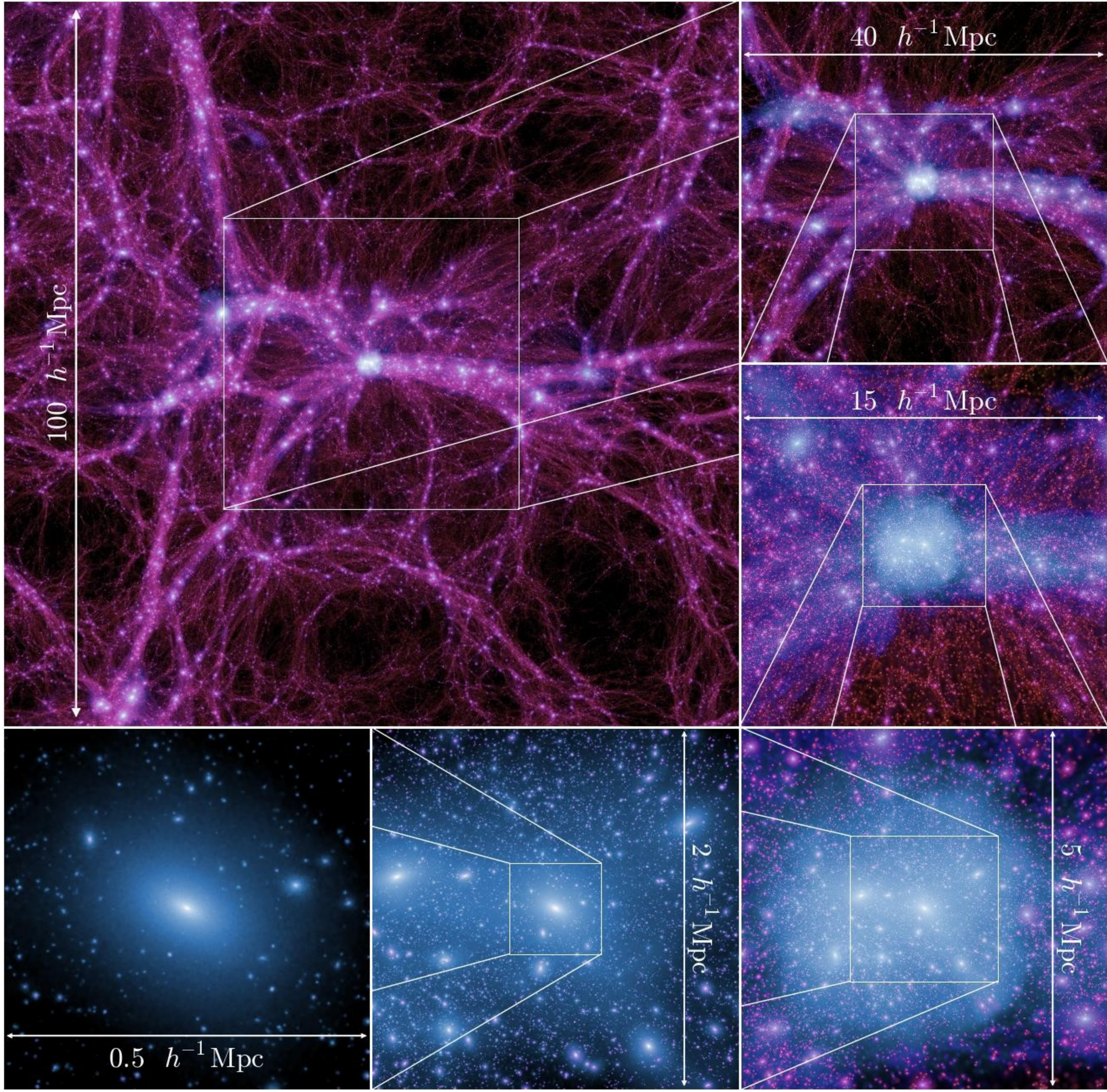
WMAP-5year



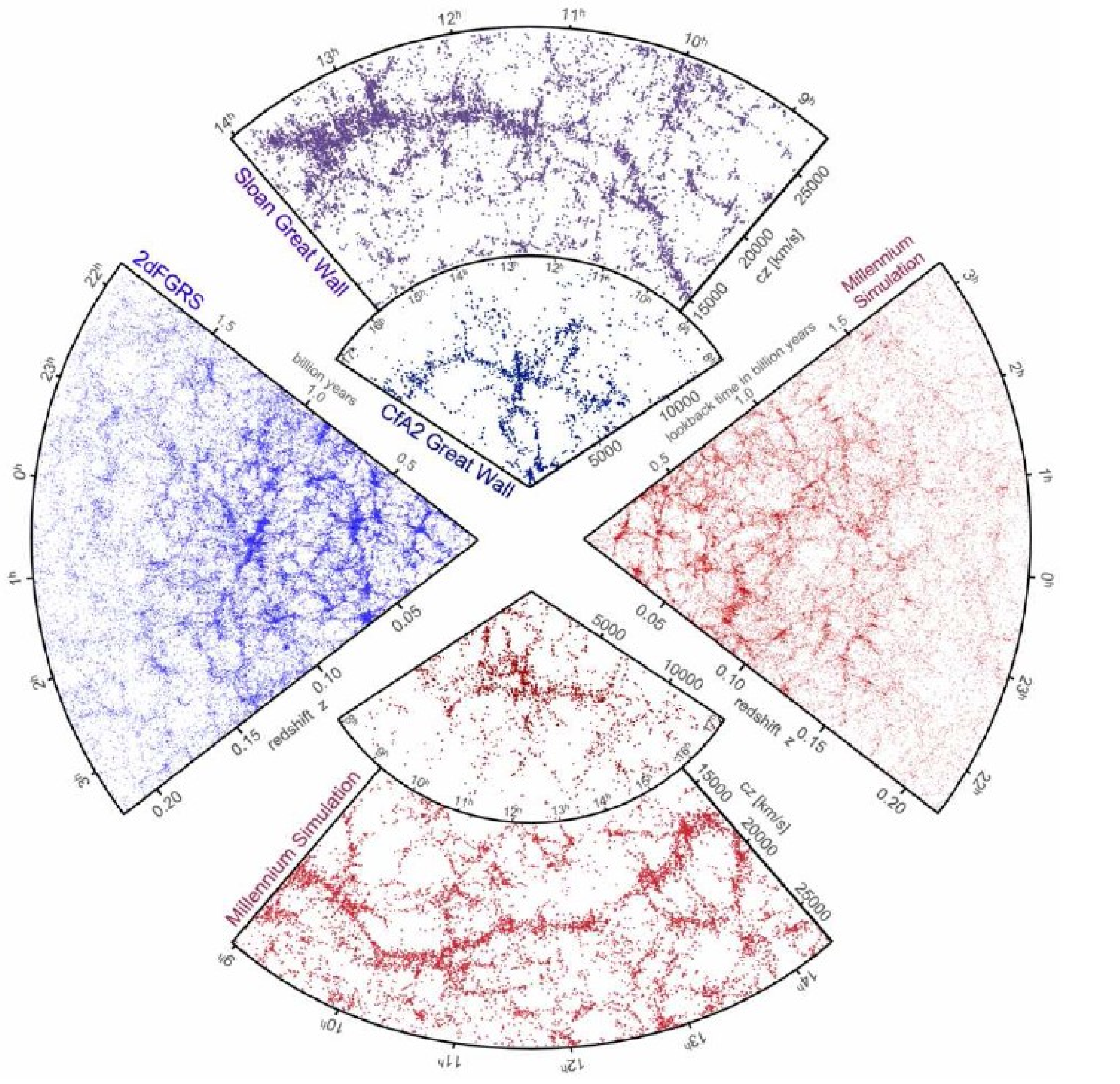
Springel et al. 2005

Millennium-II

(Boylan-Kolchin et al. 2009)



The large scale structure of the Universe



Springel, Frenk & White 2006

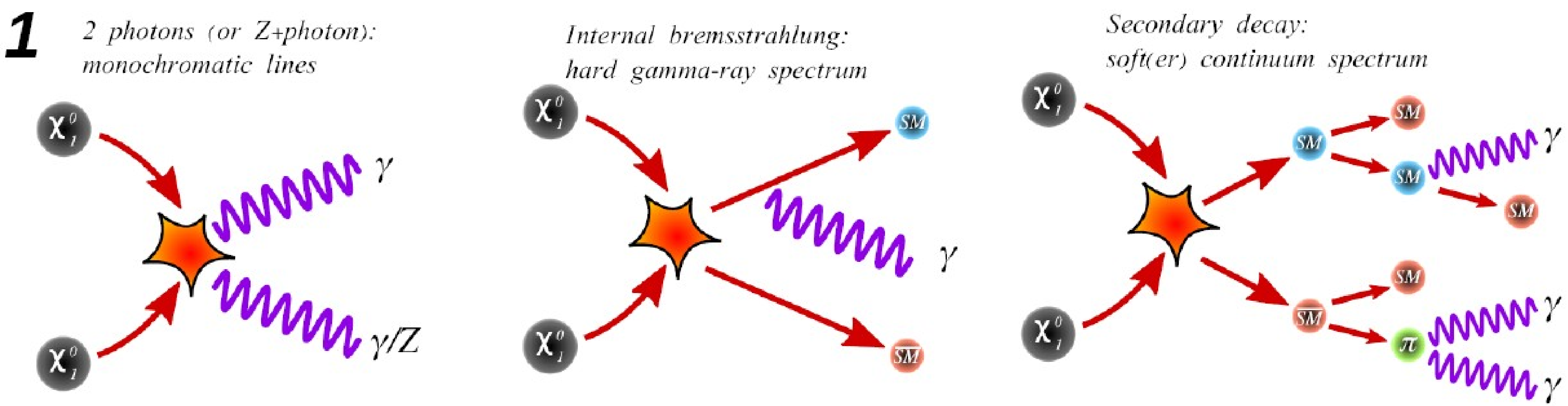
The lightest neutralino as a DM candidate

- Neutralinos (they arise in the MSSM): the neutral higgsinos and gauginos (neutral wino and bino) mix to form four mass eigenstates
- Properties of the lightest (χ_1):
  - In most of the models χ_1 is the lightest supersymmetric particle (LSP).
  - R-parity conservation in SUSY insures that χ_1 is stable.
  - It is a neutral particle with m~0.1-1.0TeV in most of the scenarios.
  - WIMPs "Weakly Interactive Massive Particles": they only interact trough the weak force and gravity with ordinary matter.
    - Majorana fermions (**they self-annihilate**).
  - Natural candidates for the CDM model of structure formation.

• Direct Searches: elastic dispersion of neutralinos with nuclei (XENON10, CDMS, Zeplin III, DAMA (positive signal)...) **Dependence on the DM phase-space distribution in the Solar System** (e.g. Vogelsberger et al. 2008).

• Indirect Searches: Based on the analysis of the byproducts produced on the annihilation of neutralinos.

- There are many possible final byproducts: positrons, neutrinos, photons...
- Photons as final states: Feynman diagrams are computed by codes such as micrOMEGAs[1] and DarkSUSY[2].



[1] http://wwwlapp.in2p3.fr/lapth/micromegas
[2] http://www.physto.se/~edsjo/darksusy/

Fig. from Scott et al. 2009

Gamma-ray emissivity

- In general, the volume emissivity of photons (energy of photons produced per unit volume, time and energy range) can be written as:

$$\epsilon_\gamma = E_\gamma \frac{dN_\gamma}{dE_\gamma} \frac{\langle \sigma v \rangle}{2} \left[\frac{\rho_\chi}{m_\chi} \right]^2 ,$$

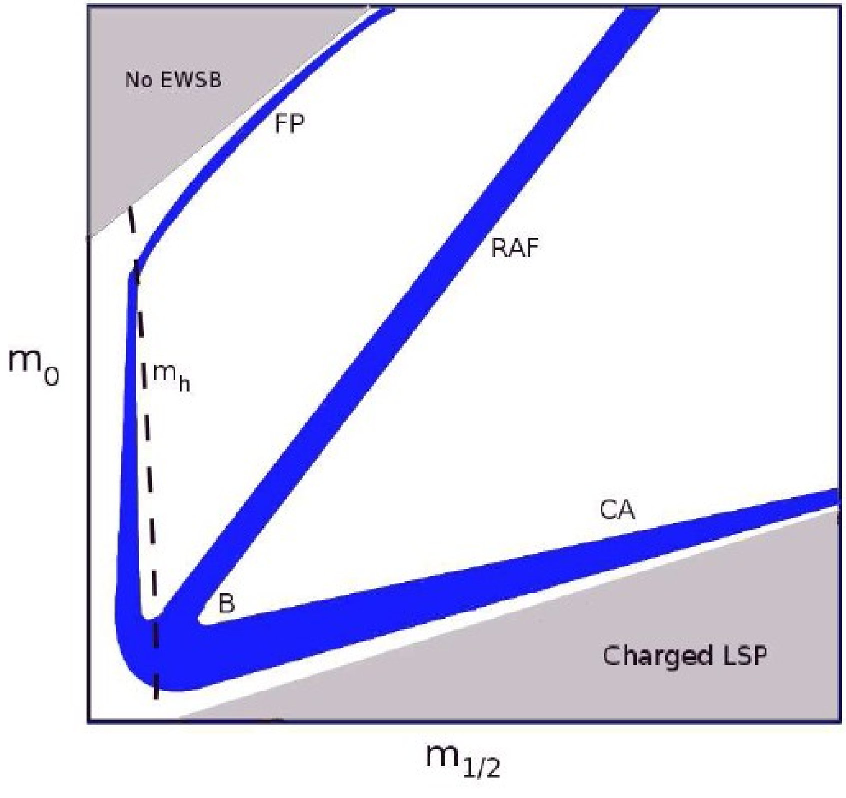
- SUSY properties of the lightest neutralino (SUSY factor):

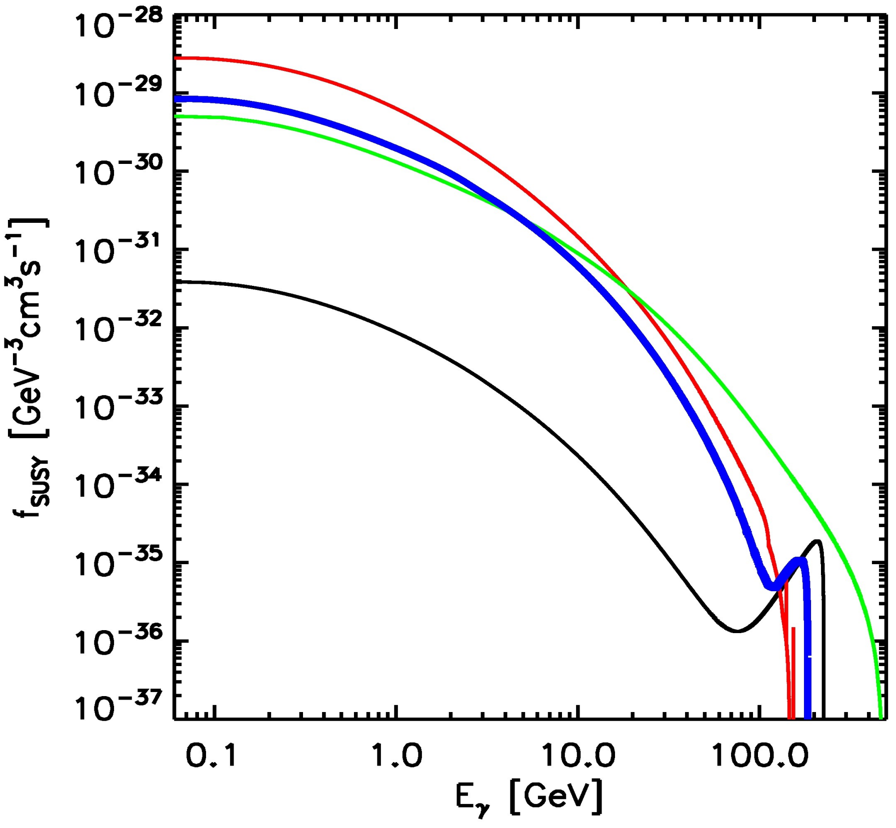
$$f_{SUSY} = \frac{dN_\gamma}{dE_\gamma} \frac{\langle \sigma v \rangle}{m_\chi^2}$$

- The density squared dependence is connected to the properties of the neutralino as dark matter (astrophysical factor).

SUSY factor

- Analysis of the mSUGRA (gravity-mediated SUSY breaking) parameter space:
- Only 5 parameters: m_0, $m_{1/2}$, A_0, $\tan\beta$ and sign of μ
- Only relic abundance allowed regions: $\Omega_\chi = \Omega_{DM}$



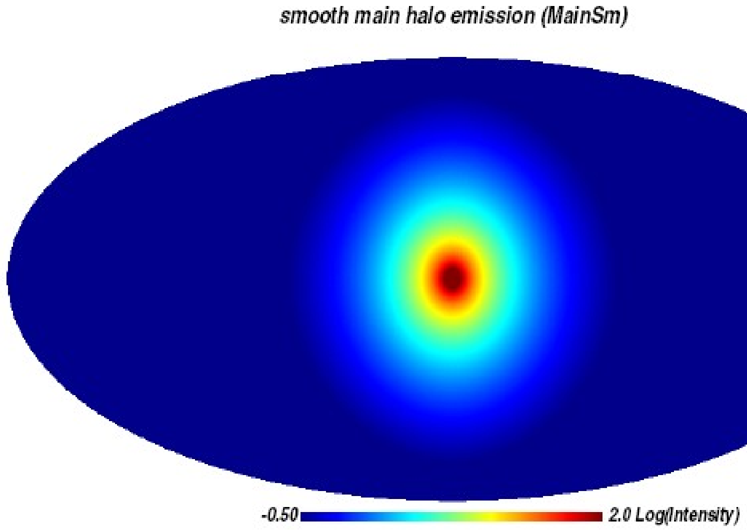


Astrophysical factor

- For a given region of volume V, the gamma-ray luminosity is proportional to:

$$L_\gamma \propto \int_V \rho_\chi^2(\vec{x})\, d^3x$$

- Regions of high DM density are promising in the search for the gamma-ray signal (GC, satellites..)
- For a smooth DM halo (Springel et al. 2008): $L_\gamma \propto \frac{V_{max}^4}{r_{half}}$

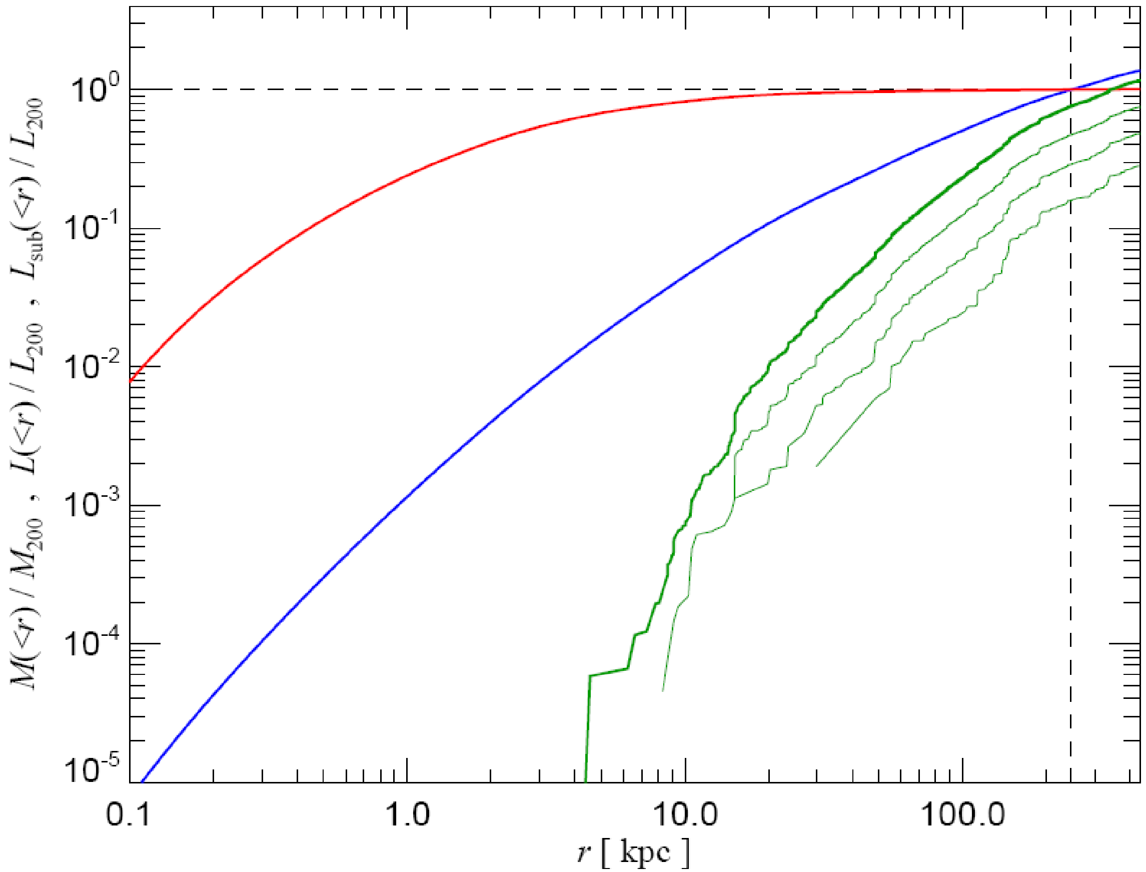


Springel et al. 2008

- Virgo Consortium's Aquarius Project (Simulation of a MW-like halo).

- For the highest resolution:
  - M_h=1.84x10^{12} Msun
  - m_{DM} =1712 Msun
  - ε = 20pc

Role of substructures



Springel et al. 2008

- Substructures within haloes have a significant role for external observers. Their contribution to the total luminosity can be as much as ~232 times the contribution of the smooth component (Springel et al. 2008).

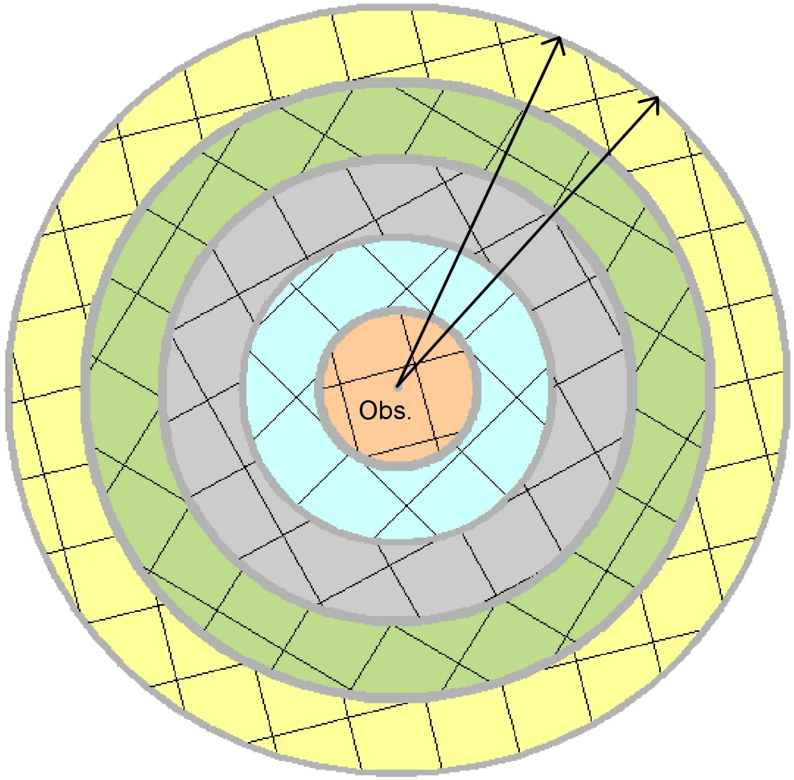
EGB radiation from DM annihilation

- Energy of photons per unit area, time, solid angle and energy range received by an observer located at z=0.

$$I_{\gamma,0} = \frac{1}{4\pi} \int \epsilon_{\gamma,0}(E_{\gamma,0}(1+z), z) \frac{dr}{(1+z)^4},$$

- Contribution from all dark matter structures along the line of sight of the observer.
- Main goal: To produce sky maps of the EGB radiation coming from the annihilation of neutralinos by simulating the backwards light cone of the observer using cosmological N-body simulations.
- Luminosity from resolved individual halos and subhalos is computed using the scaling law from Springel et al. 2008

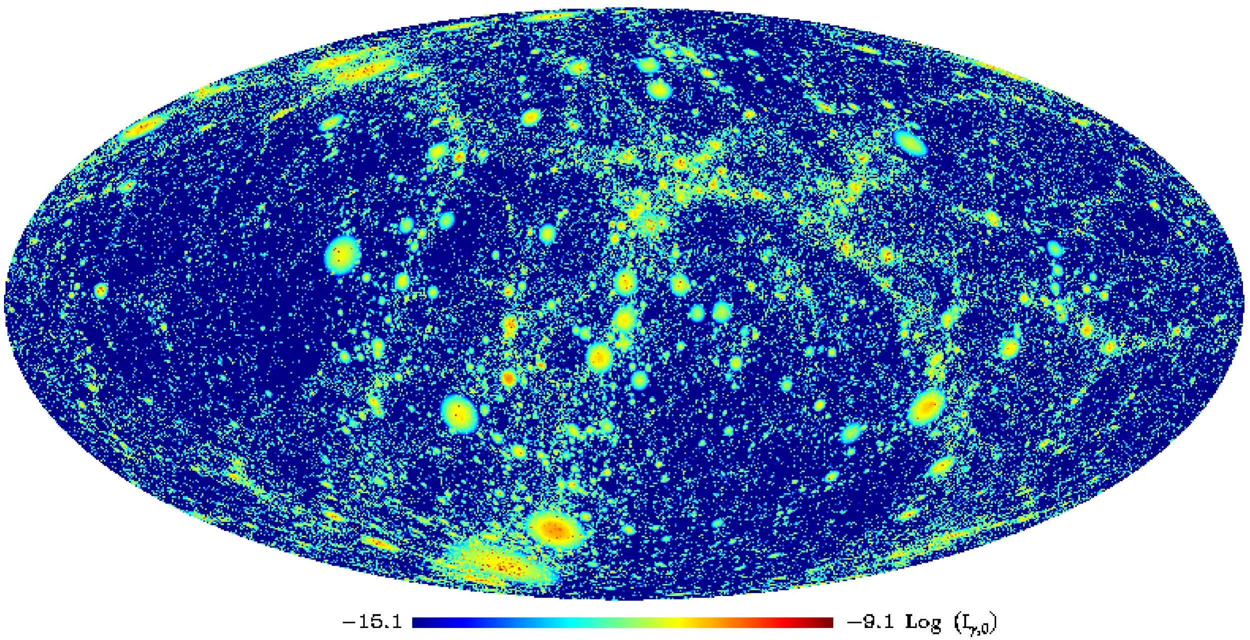
Light-cone simulation



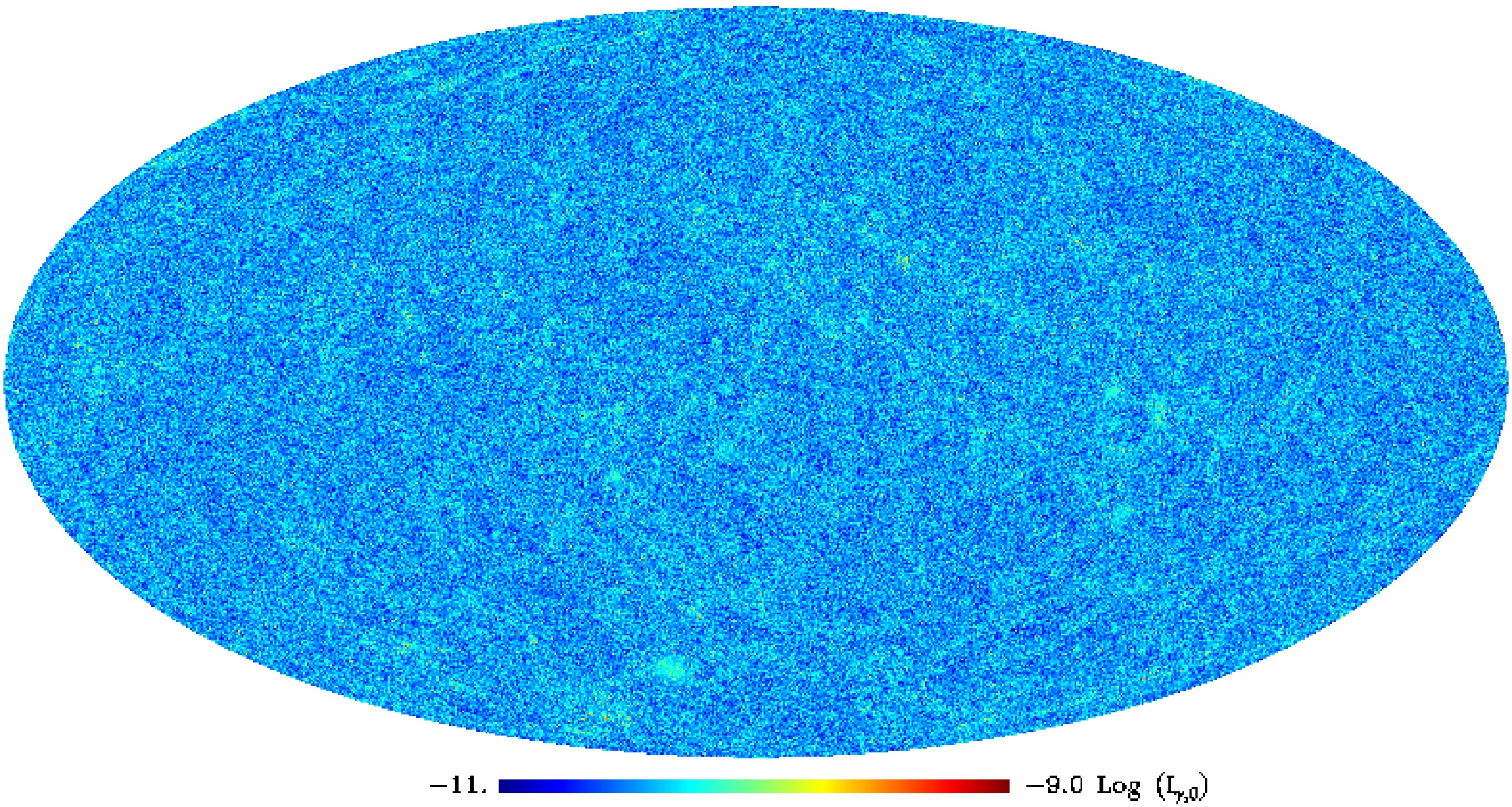
Value per pixel:

$$I_{\gamma,0}(\Delta\Omega_{\rm pix}) = \frac{1}{8\pi}\sum_{h\epsilon\Delta\Omega_{pix}} L_h w(d_h, r_h) E_{\gamma,0} f_{\rm SUSY}(z_h)|_{E_{\gamma,0}}$$

Local structures (First shell, 68Mpc)



All-sky maps

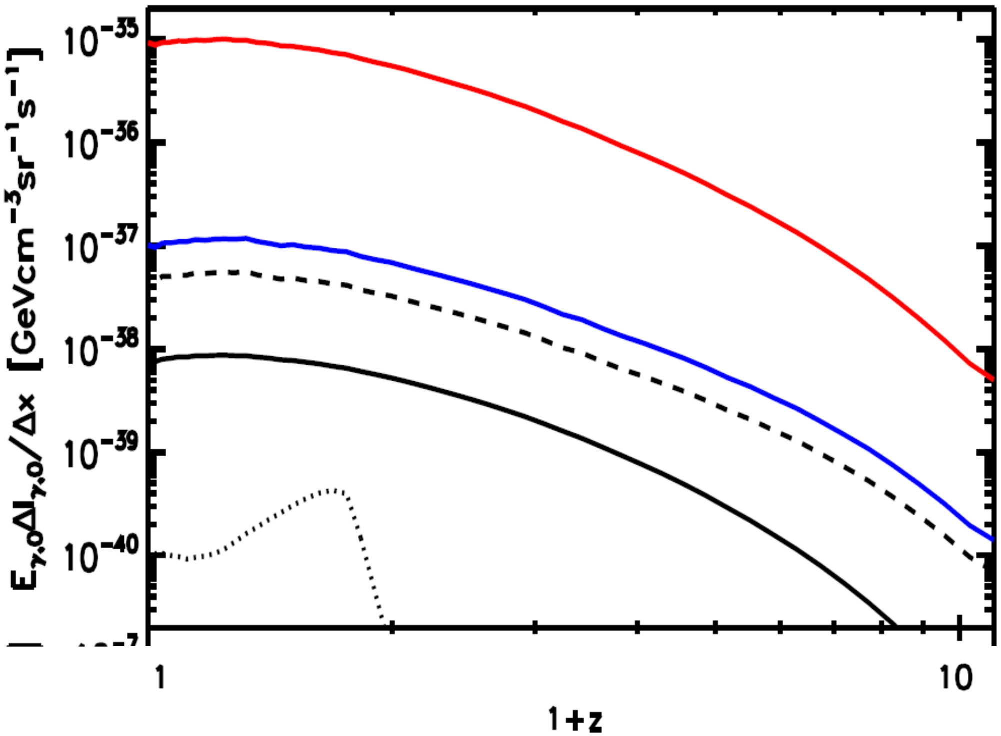


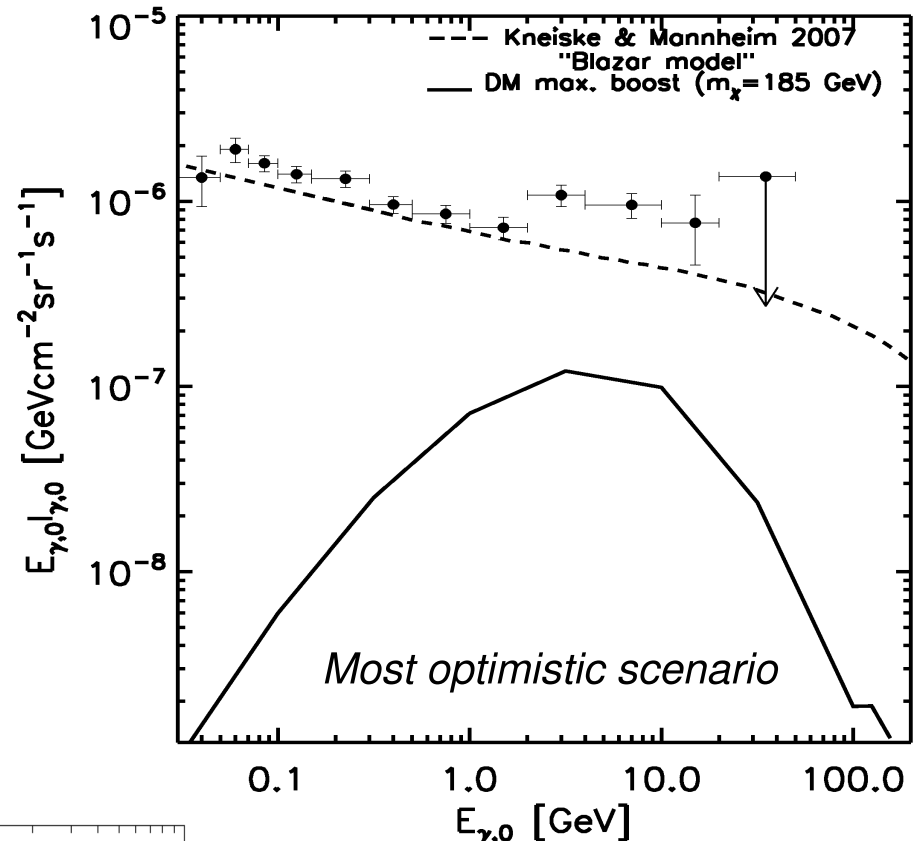
$N_{pix} = 12(512)^2 \sim 3\times10^6$

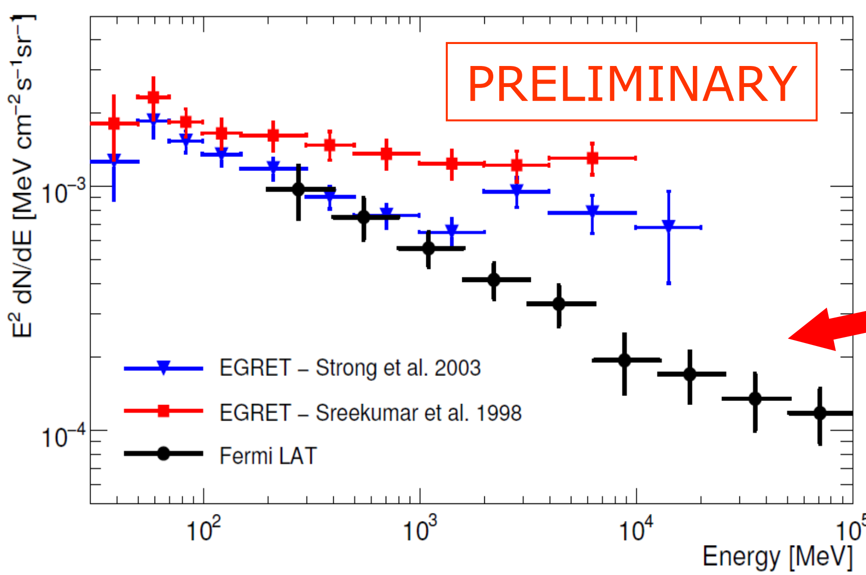
Ang. Res (FERMI) ~ 0.115°

Extrapolation for unresolved halos down to earth masses (~2 orders of magnitude uncertainty)

Isotropic component



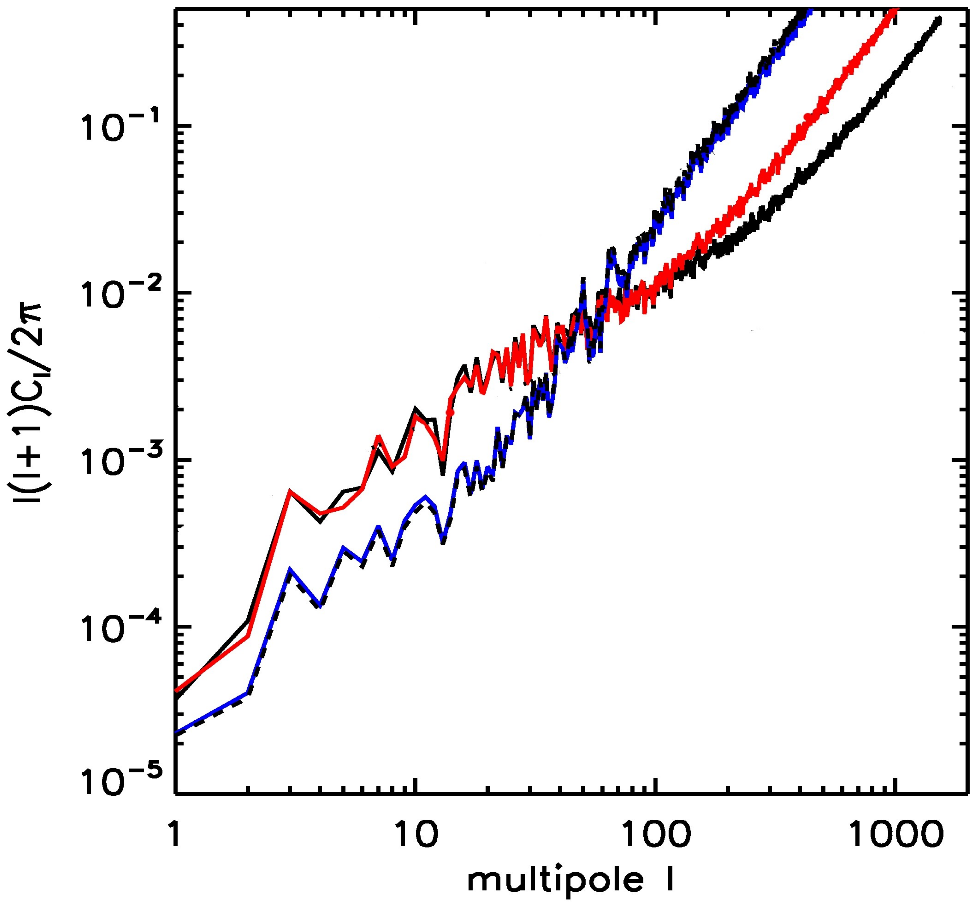


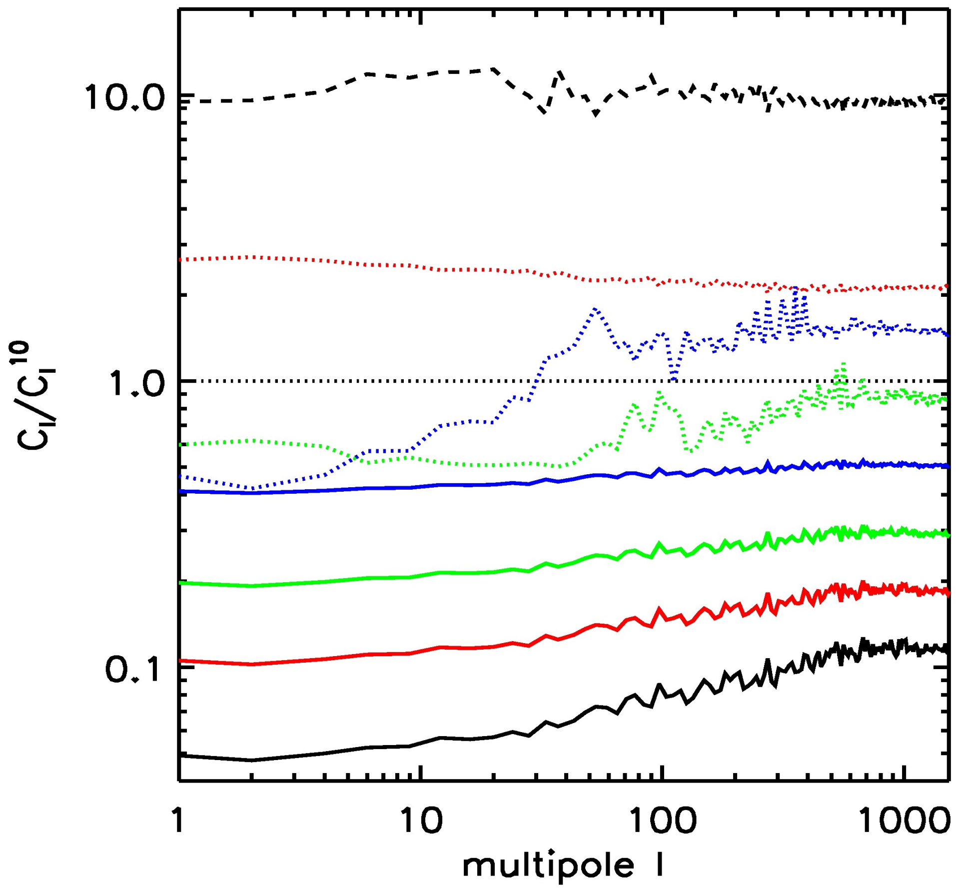


FERMI

Anisotropic component

$$\Delta_{I_{\gamma,0}}(\theta,\phi) = \frac{I_{\gamma,0}(\theta,\phi) - \langle I_{\gamma,0}\rangle}{\langle I_{\gamma,0}\rangle} = \sum_{l=0}^{\infty}\sum_{m=-l}^{m=l} a_{lm} Y_{lm}(\theta,\phi)$$



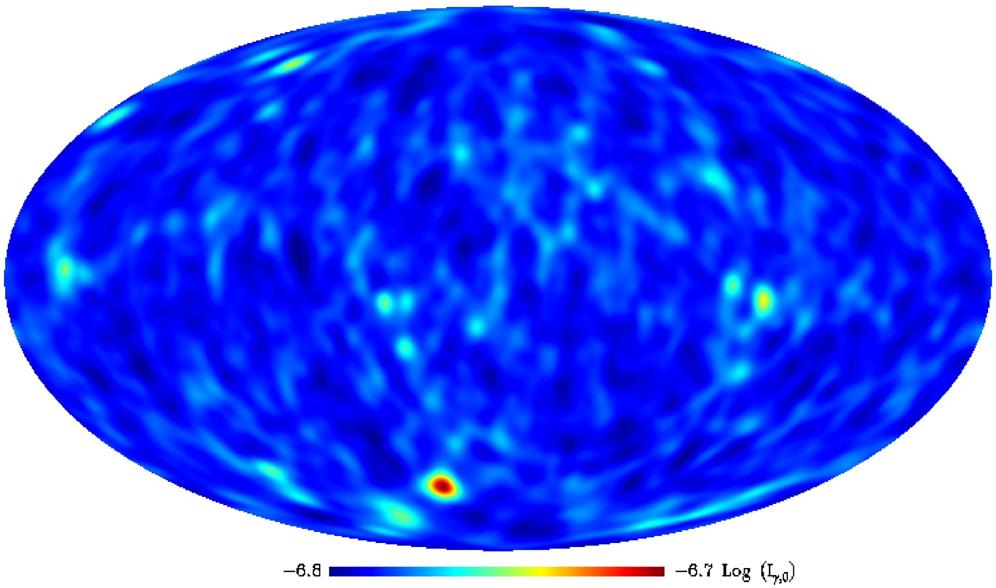


$$C_l = \frac{1}{2l+1}\left(\sum_m |a_{lm}|^2\right)$$

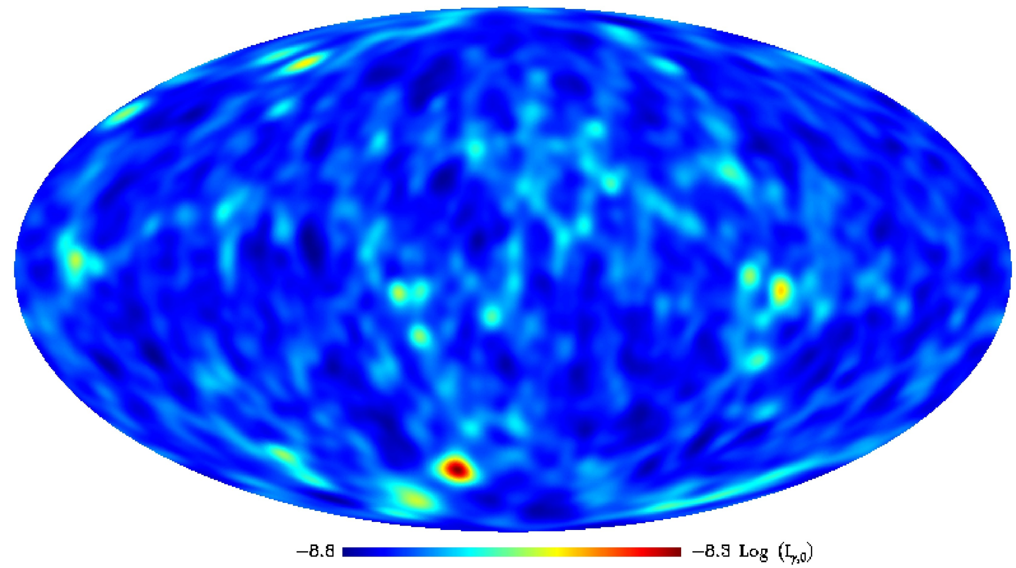
The energies are: 0.1,0.32,1.0,3.2 (solid black, red, green and blue), 10, 32, 100, 125 (dotted black, red, green and blue) and 156 GeV (dashed black).

Color maps

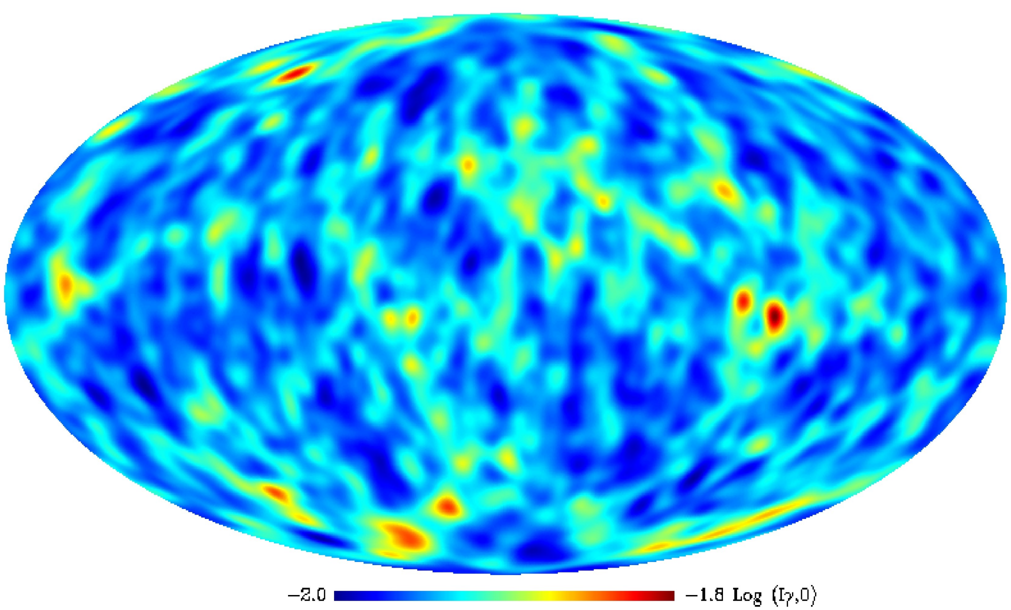
0.1 GeV



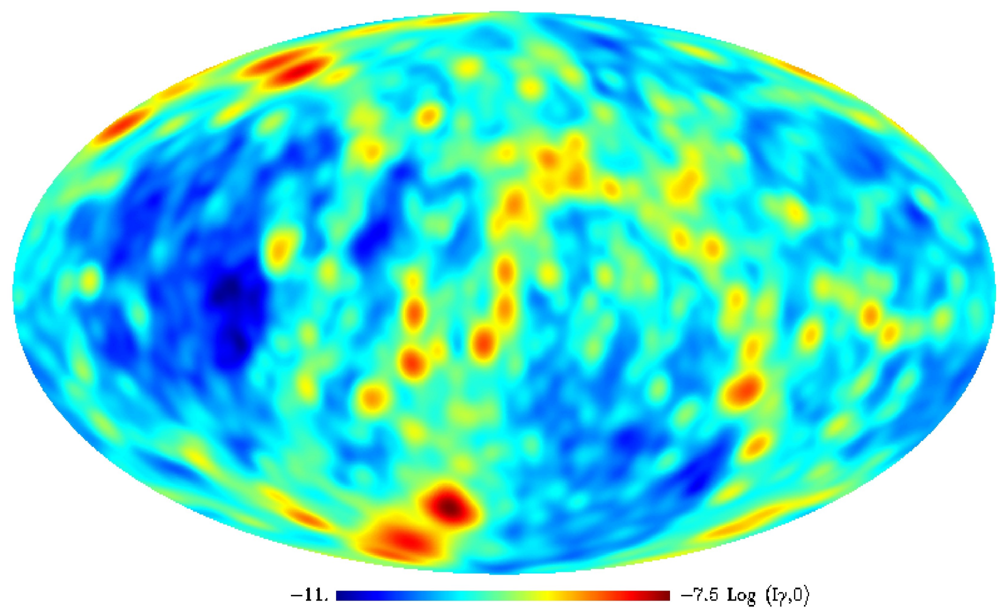
32 GeV



Map ratio



0.1 GeV at z=0



Summary and Conclusions

- Simulated all-sky maps of the EGB from annihilation including:
  - Normalization given by a mSUGRA model compatible with relic density (continuum, monochromatic and IB photon spectrum), uncertainty of ~2-3 orders of magnitude.
  - Dark matter spatial distribution using Millennium-II simulation (resolved and unresolved components), uncertainty of ~2 orders of magnitude in extrapolation.
- Isotropic component ~1 order of magnitude below observed signal in most optimistic scenario.
- Anisotropic component has distinctive features of the gamma-ray production by annihilation.
- Energy dependence of the anisotropy can be exploited to produce “color” maps to enhance cosmic large-scale structures at low redshifts.
- The technique can be used to simulate the contribution of other sources like normal galaxies, blazars, etc.