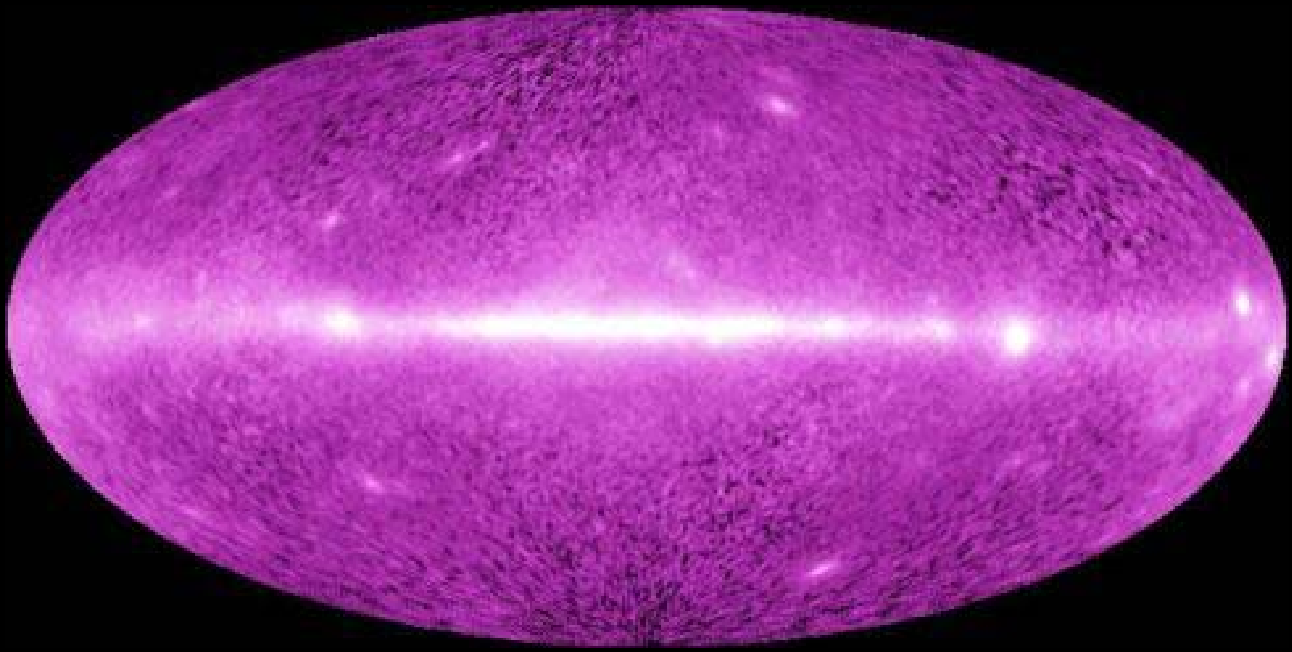
Signatures of Dark Matter in the Diffuse γ-rays



Pasquale D. Serpico, Center for Particle Astrophysics

Fermilab

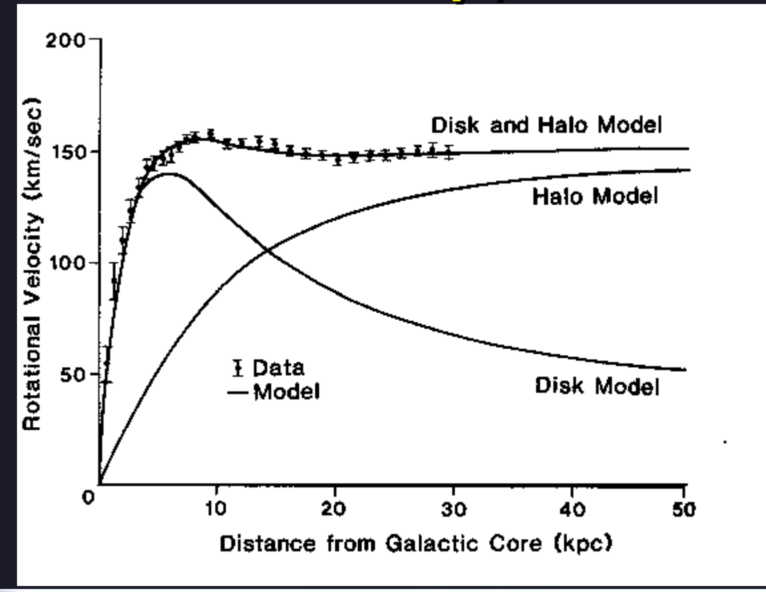
Dip. Scienze Fisiche & INFN, Napoli – 15 Marzo 2007

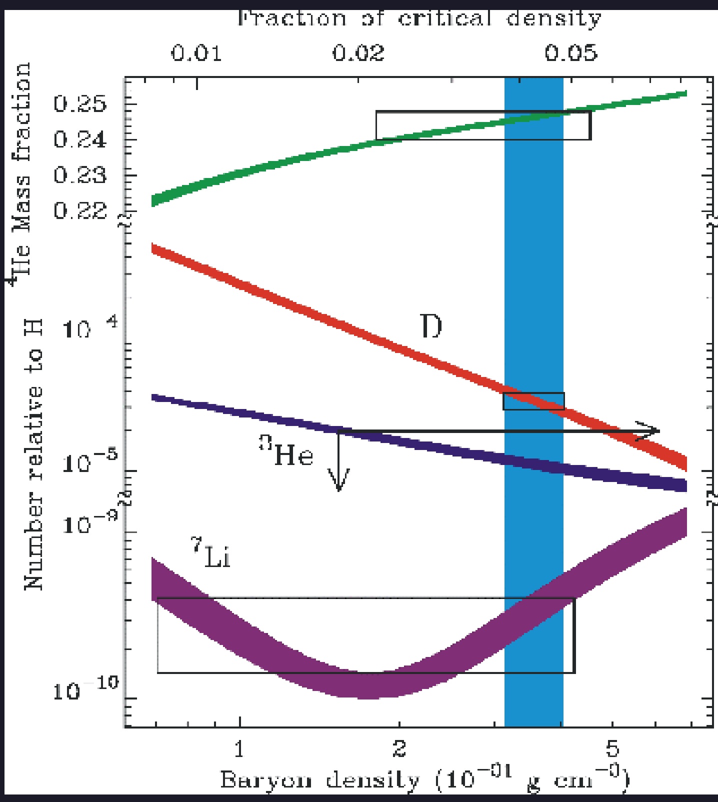
Outline

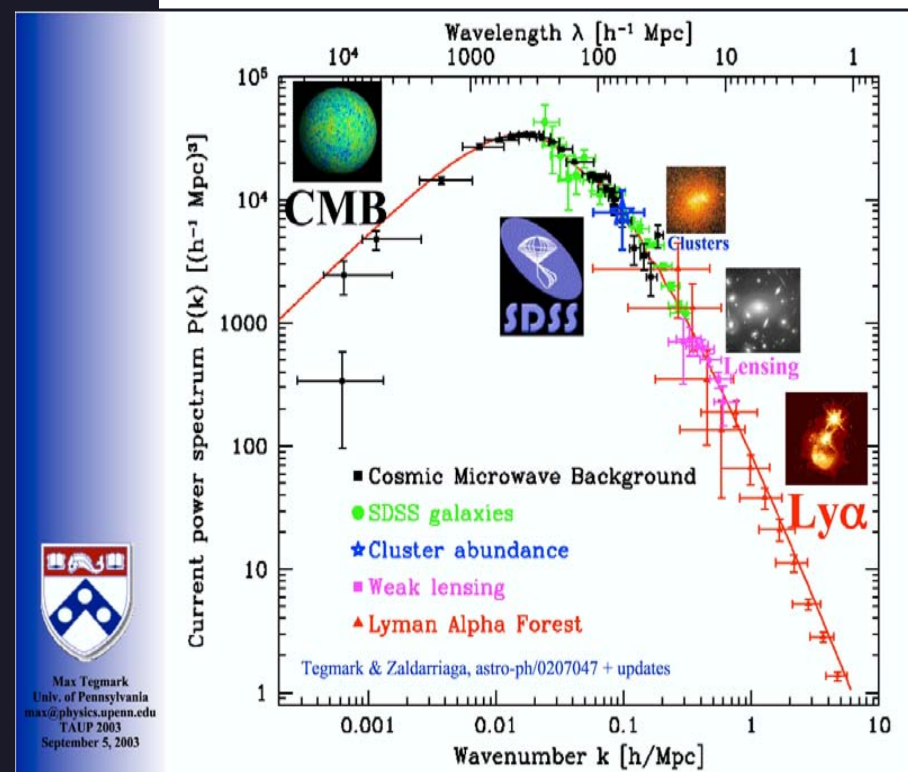
- ✓ Introduction
- ✓ Indirect Detection
- ✓ Galactic vs. Extragalactic
  - ❑ Relative Intensity
  - ❑ Extragalactic angular features
  - ❑ Galactic angular features
- ✓ Prospects for detection (GLAST)
- ✓ Conclusions

Introduction

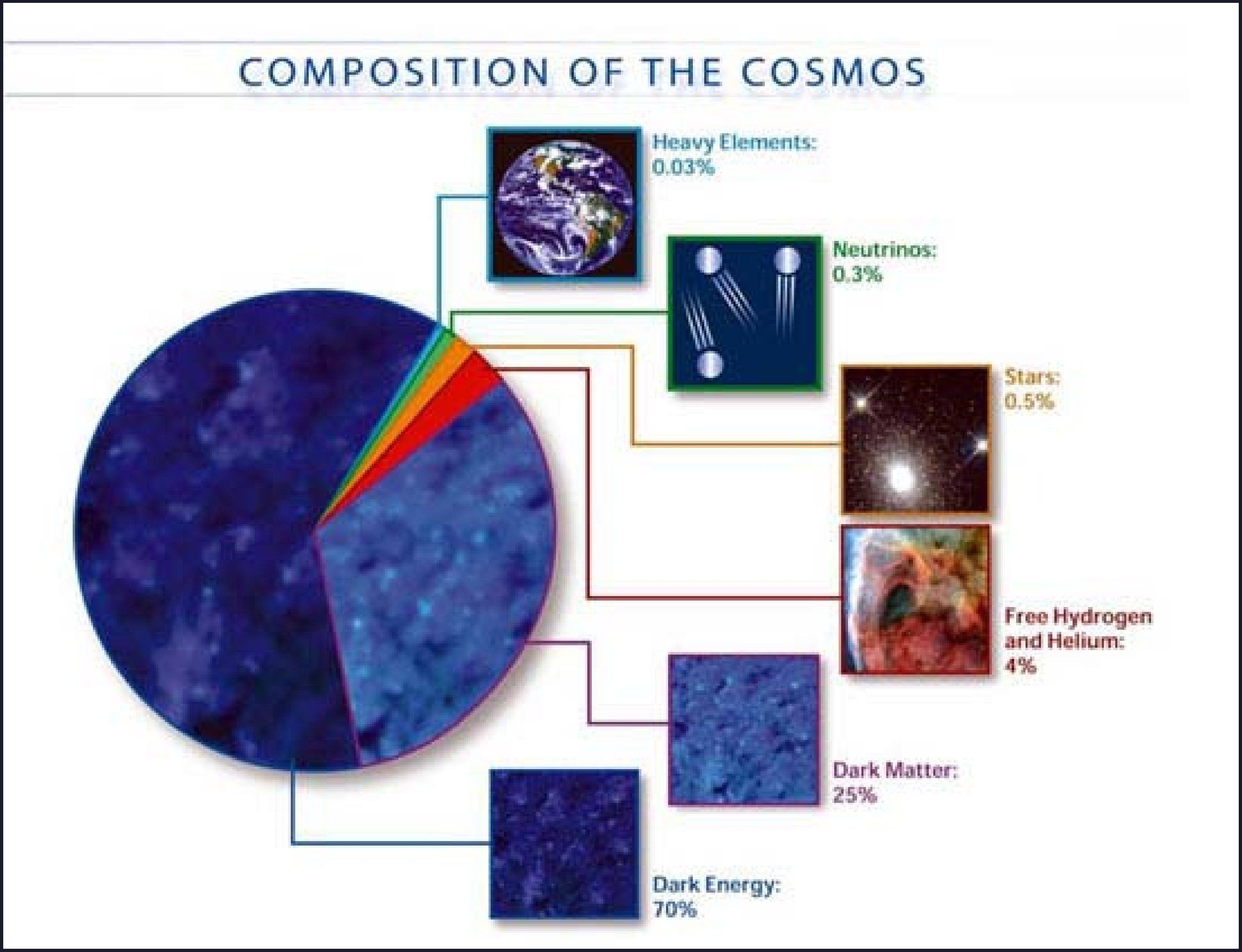
Dark Matter Problem(s), since F. Zwicky,'33



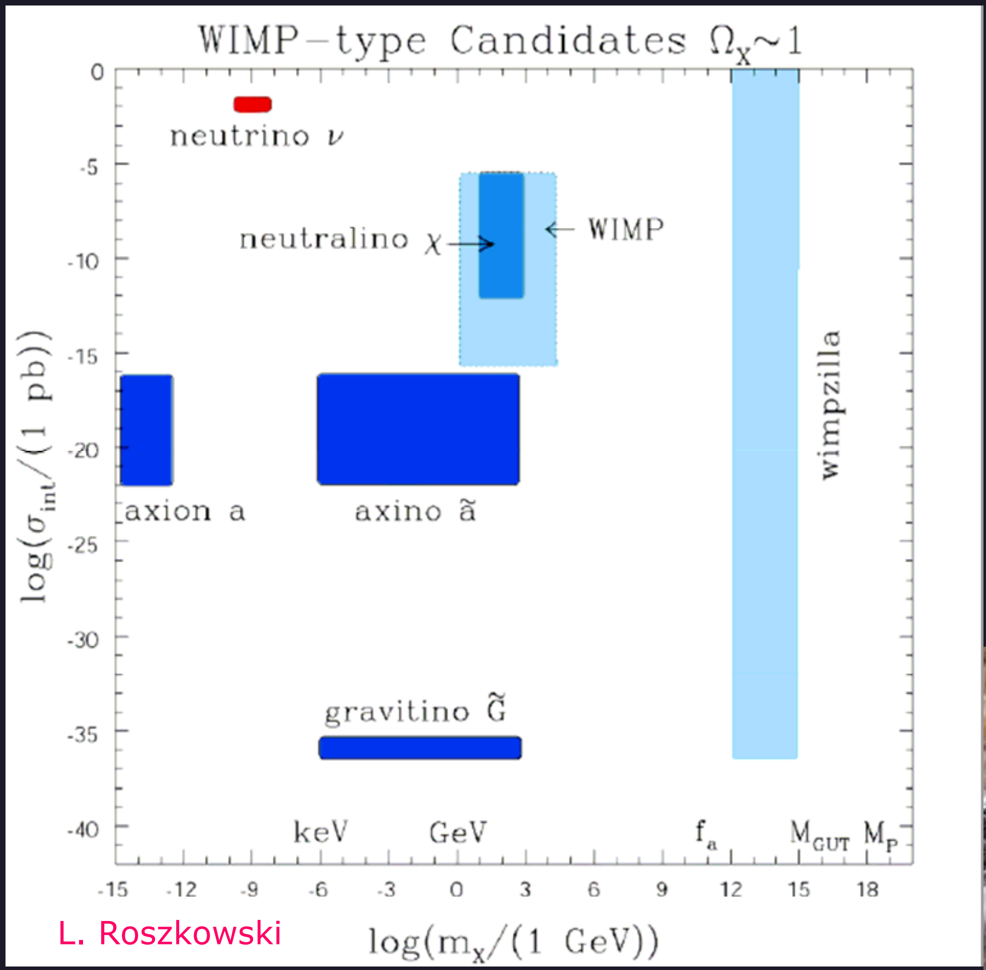




The accurate Recipe of our Ignorance



What is Dark Matter?



- ✓ It’s cold
- ✓ It’s dark
- ✓ Physicists at the most important Labs care for it
- ✓ It’s non-baryonic! New Physics!

A reasonable bet: WIMPs

✓ The Weakly Interacting Massive Particle ”miracle”: thermal relic with EW gauge couplings & $m_{wimp} \approx 0.1\text{–}1$ TeV matches the cosmological abundance requirement, $\Omega_{wimp} \approx 0.25$

✓ EW symmetry breaking related with DM? Possibly, e.g. neutralino in SUSY, KK states in extra-dimension theories

✓ EW-related candidates interesting experimentally: rich phenomenology, higher chances of detection, many techniques

➢ Warning: keep in mind other possibilities (Axions, SHDM, SuperWIMPS, MeV DM, sterile neutrinos…)
Peculiar signatures, ad hoc searches

WIMP detection techniques

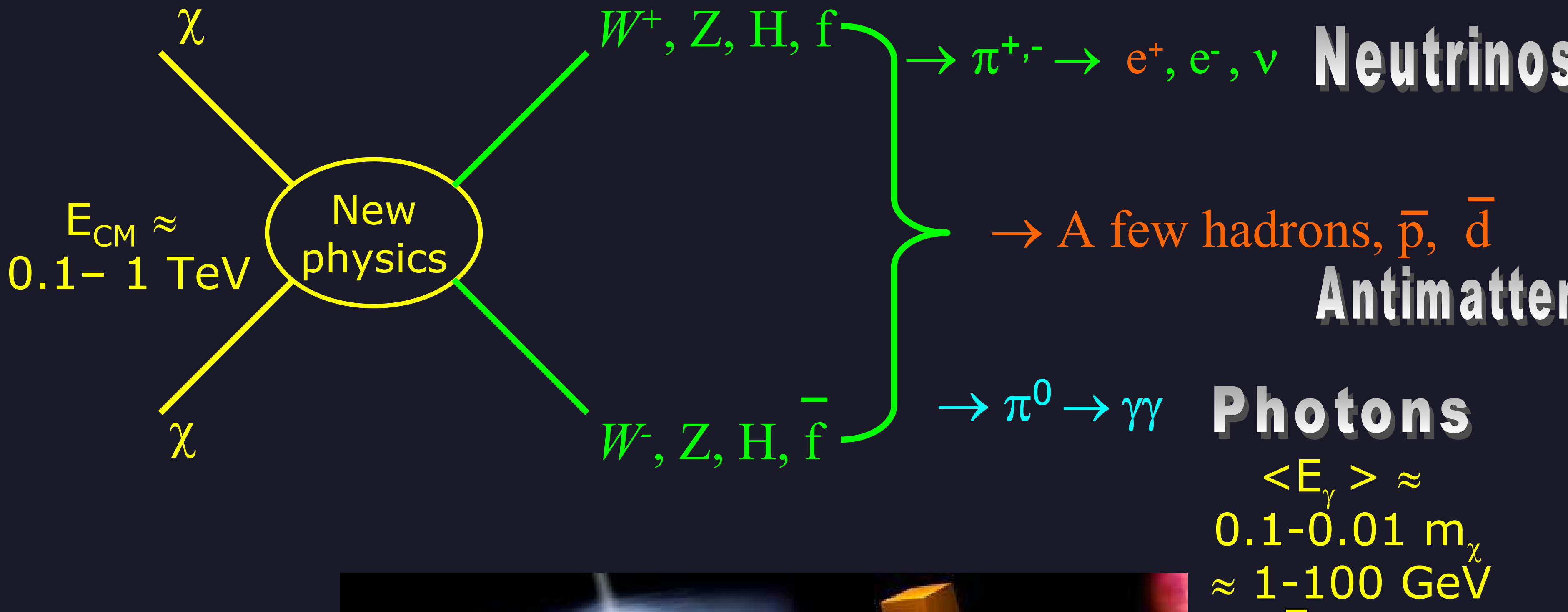
Experiment	*Source*	*Interaction*	*Channel*
Direct (CDMS…)	Local (crossing Earth surface)	WIMP-nucleus scattering	Phonons
Indirect (GLAST…)	Earth, Sun, Galaxy, Cosmos	WIMP pair annihilation	γ,ν, Antimatter
Collider (LHC,…)	Controlled production	WIMP pair production	$\not{E}$

Advertisement: INFN Napoli is heavily involved in programs in all the three techniques, directly related to DM searches as one of the primary goals (Warp, Pamela) or serendipiteously (ARGO, AUGER, NEMO, LHC)

Sector where interplay among experimental and theoretical physicists is crucial

Indirect Detection: shining light on the dark matter via gamma rays

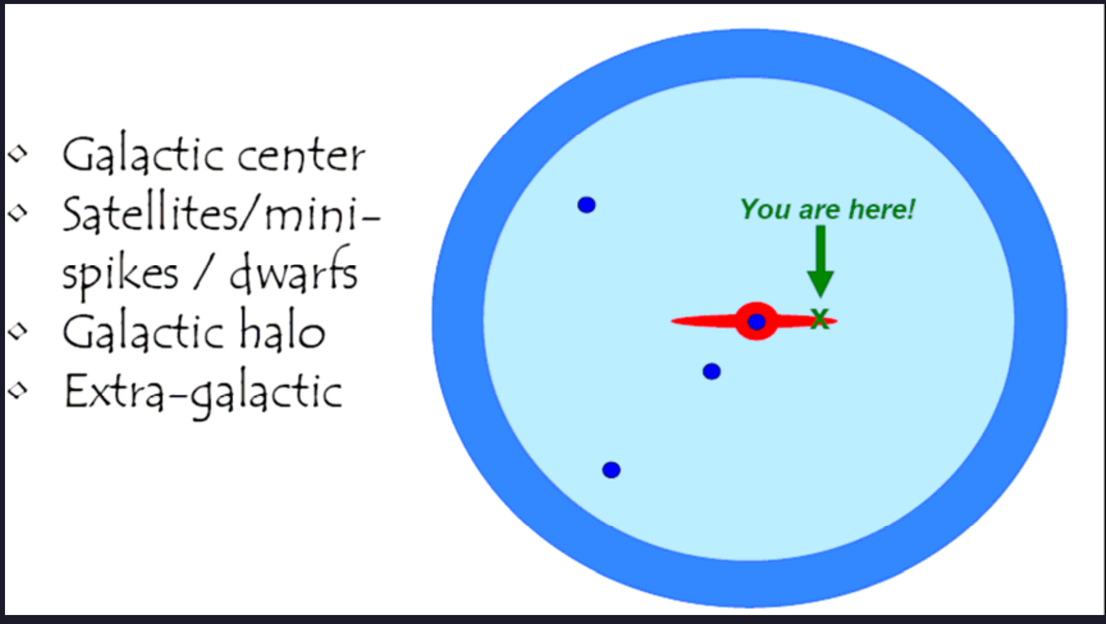
Indirect detection (“Susy in the sky”?)



Where to look for Gammas?

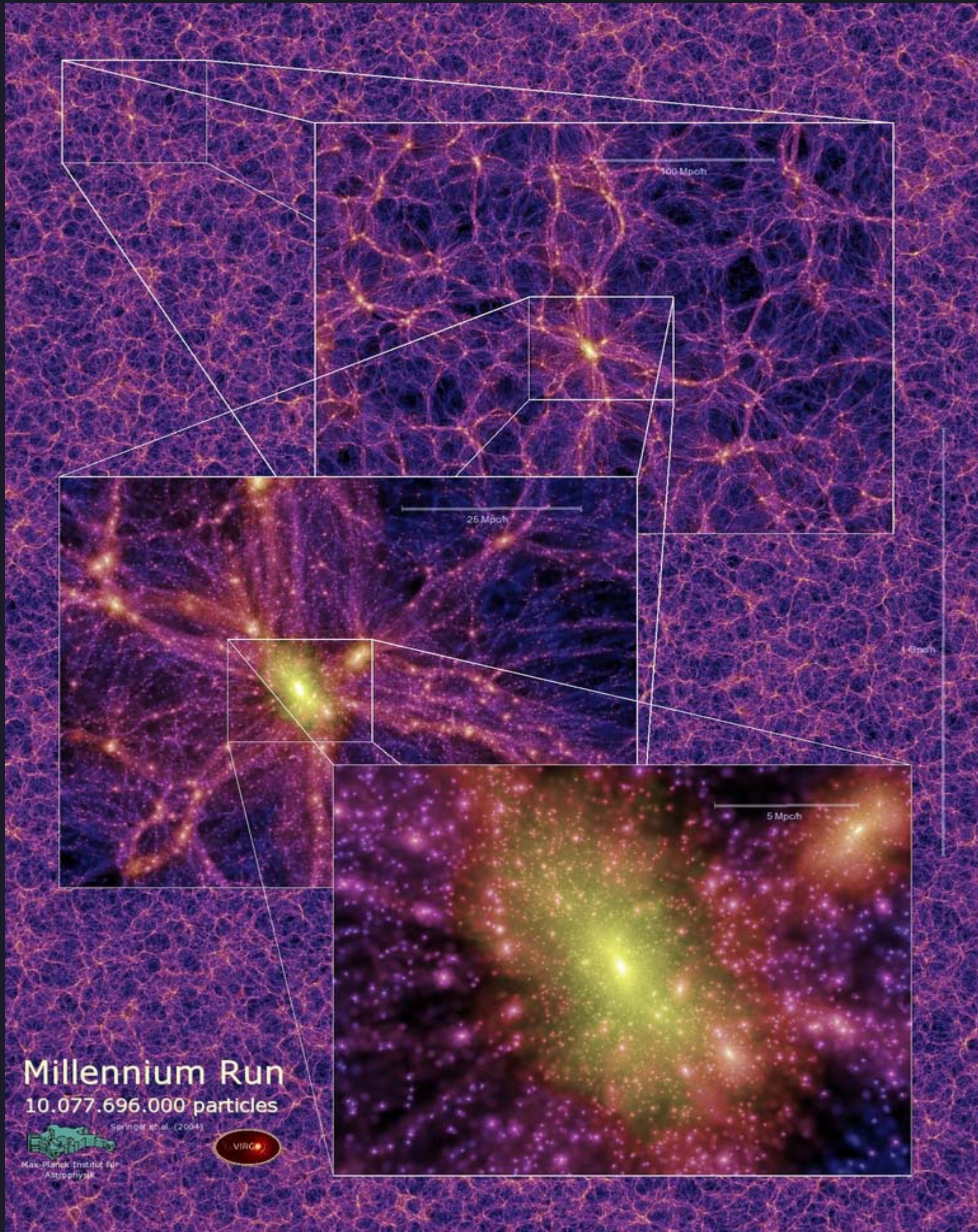
Target	Advantage	Challenges
Spectral line E= m$_\chi$ anywhere	Smoking gun	Loop process, suppressed
Galactic center	High intensity	DM profile, astrophysical foregrounds
Satellites, μ-halos…	Low background	Low statistics, DM profile
Diffuse galactic & extragalactic	High statistics	Cosmological uncertainty, astrophysical foregrounds

angular *AND* energy information



The hierarchical structure formation paradigm

Structures in the Universe results from the gravitational amplification of small, primordial density fluctuations. The collapse is driven by cold DM, and smaller and more compact structures form first. They merge to build up bigger galaxies, and bigger galaxies collide and merge to make the largest galaxies… the largest superclusters are the youngest bound strucures.

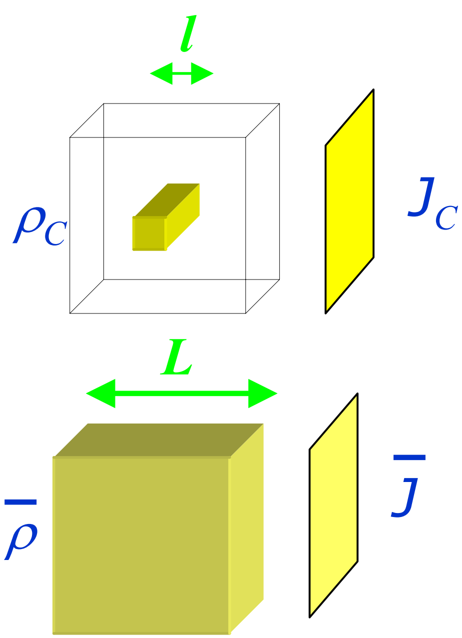


Is this important for DM detection via gammas?
Unfortunately, Yes

Why should we care? A simple argument

$$I_c \propto \rho_c^\kappa \, l = \bar{\rho}^\kappa \left(\frac{L}{l}\right)^{3\kappa} l = \bar{\rho}^\kappa \left(\frac{L}{l}\right)^{3\kappa-1} L$$

$$I_c = \bar{I}\left(\frac{L}{l}\right)^{3\kappa-1} \qquad J_c = \left(\frac{L}{l}\right)^{3\kappa-3} \bar{J} = \left(\frac{\rho_c}{\bar{\rho}}\right)^{\kappa-1} \bar{J}$$

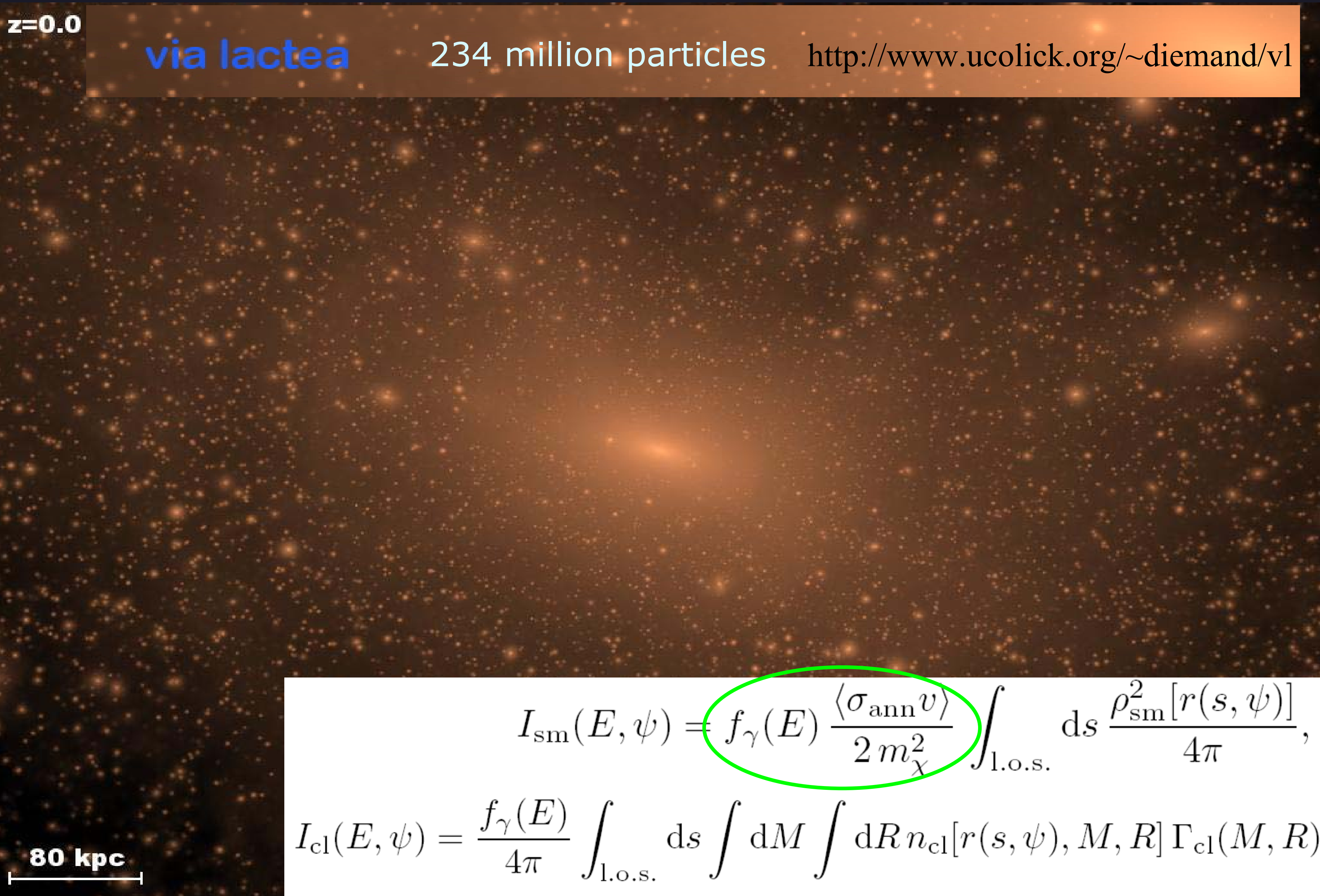


For annihilating DM, not only the angular pattern, but also the intensity depends on the degree of clumpiness!

$$\rho_c \, l^3 = \bar{\rho} \, L^3$$

A preliminary question: which diffuse flux dominates the average intensity?

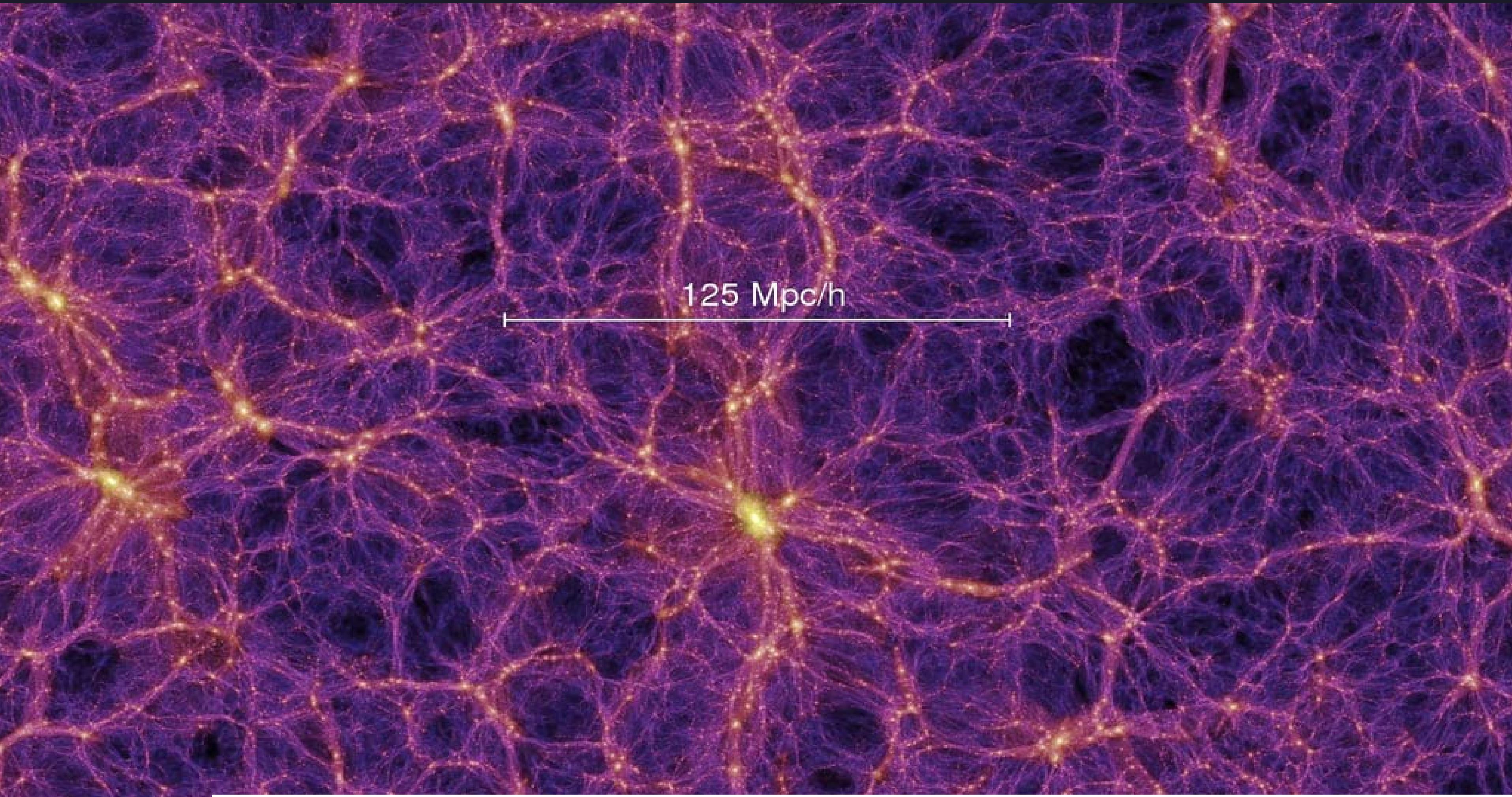
Application to the Galactic case



$$I_{\rm sm}(E,\psi) = f_\gamma(E)\,\frac{\langle\sigma_{\rm ann}v\rangle}{2\,m_\chi^2}\int_{\rm l.o.s.} {\rm d}s\,\frac{\rho_{\rm sm}^2[r(s,\psi)]}{4\pi},$$

$$I_{\rm cl}(E,\psi) = \frac{f_\gamma(E)}{4\pi}\int_{\rm l.o.s.} {\rm d}s \int {\rm d}M \int {\rm d}R\, n_{\rm cl}[r(s,\psi),M,R]\,\Gamma_{\rm cl}(M,R)$$

Application to the Extragalactic Case



$$I_{\rm ex}(E) = \frac{c}{4\pi} \frac{\langle \sigma_{\rm ann} v \rangle}{2\, m_\chi^2} \int_0^\infty {\rm d}z\, \frac{\rho_{\rm dm}^2(z)}{H(z)\,(1+z)^3}\, f_\gamma[E(1+z)]\, e^{-\tau(E,z)}$$

$$H(z) = H_0 \sqrt{\Omega_M (1+z)^3 + \Omega_\Lambda}.$$

An useful parametrization

$$\Gamma_{\rm cl}(M,R) = \int_V \mathrm{d}^3\mathbf{x} \frac{\langle\sigma_{\rm ann}v\rangle}{2\,m_\chi^2}\rho_{\rm cl}^2(\mathbf{x}) \equiv \bar{\rho}_{\rm cl}^2 V\,S\,\Pi = \bar{\rho}_{\rm cl} M\,S\,\Pi$$

$$\int \mathrm{d}M \int \mathrm{d}R\, n_{\rm cl}[r(s,\psi),M,R]\,M = \xi\,\rho_{\rm sm}[r(s,\psi)].$$

Ansatz

ζ

$$I_{\rm gal}(E,\psi) = \frac{1}{4\pi} f_\gamma(E)\,\Pi \int_{\rm l.o.s.} \mathrm{d}s\,\rho_{\rm sm}[r(s,\psi)] \times \left(\rho_{\rm sm}[r(s,\psi)] + S\,\xi\,\bar{\rho}_{\rm cl}\right)$$

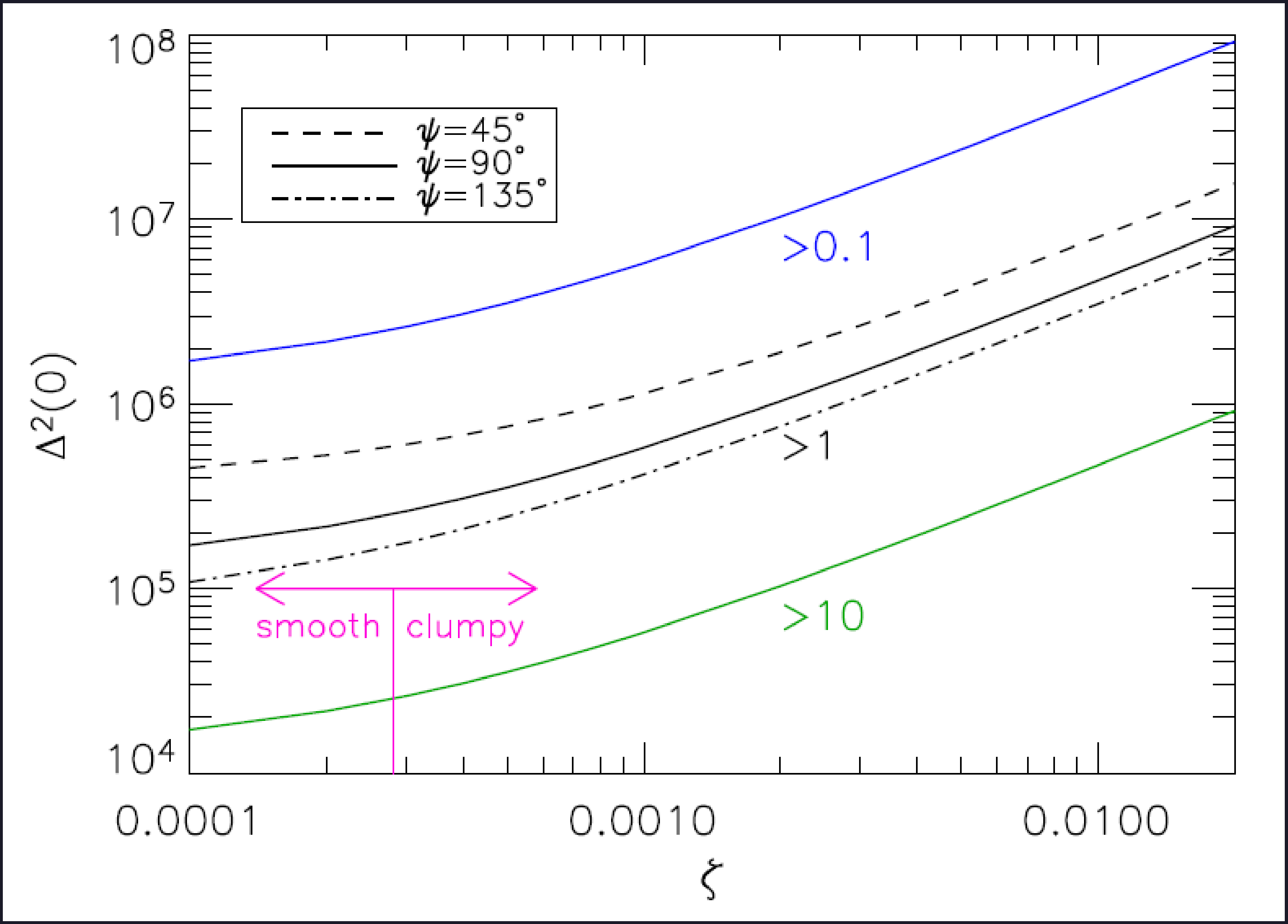
$$\rho_{\rm dm}^2(z) \equiv \left(\frac{\rho_{\rm dm,0}}{\rho_{c,0}}\right)^2 \rho_{c,0}^2(1+z)^6\Delta^2(z) = \Omega_{\rm dm}^2\left(\frac{3H_0^2}{8\pi G_N}\right)^2(1+z)^6\Delta^2(z)$$

$$\Delta^2(z) = \frac{\Delta^2(0)}{(1+z)^3}$$

Ansatz

$$I_{\rm ex}(E) = \frac{c}{4\pi}\frac{\langle\sigma_{\rm ann}v\rangle}{2\,m_\chi^2}\Omega_{\rm dm}^2\,\rho_{c,0}^2\,\Delta^2(0)\int_0^\infty \mathrm{d}z\,\frac{f_\gamma[E(1+z)]\,e^{-\tau(E,z)}}{H_0\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}$$

Results

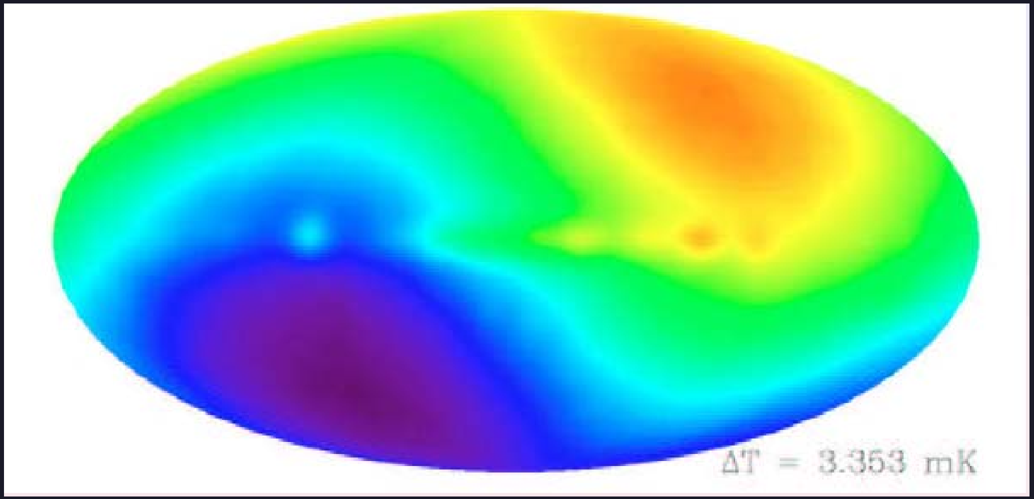


D.Hooper and PS, astro-ph/0702328

Extragalactic dominance Signatures

Cosmological Compton-Getting Effect

✓ The solar system is moving (u=368 km/s) with respect to the cosmological rest frame, as indicated by the CMB dipole



✓ As long as we collect γ's from a large number of sources at cosmological distance, sources are on average at rest

A dipole anisotropy should be visible in the HE sky with amplitude

$$[I(E)=E^2 f(E)]$$

$$A_{CCG} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = u/c\ (2 - d \ln I / d \ln E) = 0.5\%$$

M. Kachelrieß & PS, PLB 640, 225 (2006) [astro-ph/0605462]

CCG effect for γ's

✓ A detection of the CCG effect is well within the reach of GLAST (with the EGRET flux, O(10^6) CGB photons *per year* at E>GeV)
The signature has been detected in the X-ray background

S.P. Boughn, et al. ApJ 580, 672 (2002) [astro-ph/0208153]

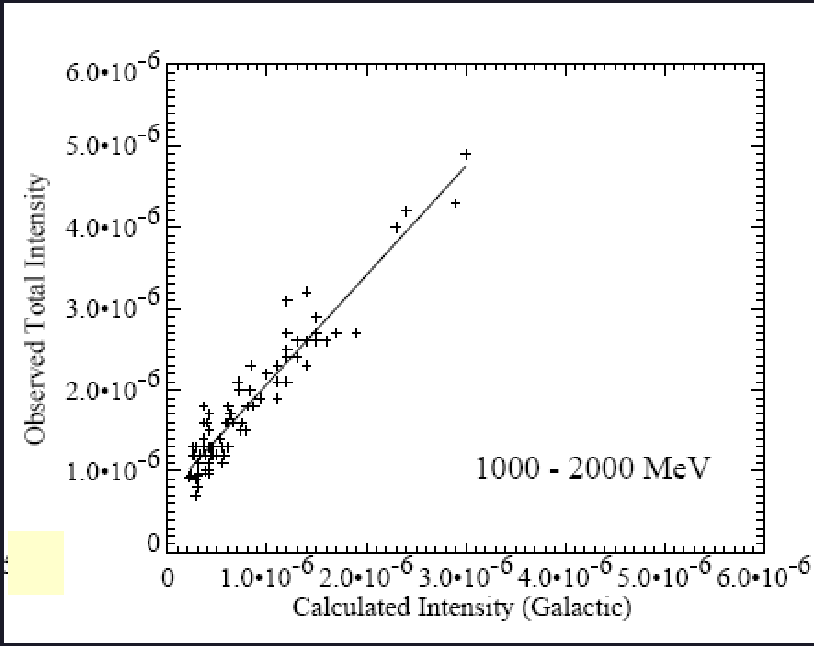
C.A. Scharf et al ApJ 544, 49 (2000) [astro-ph/9908187]

✓ CCG effect would allow one to extract the truly extragalactic fraction of the CGB, basically in a model independent way

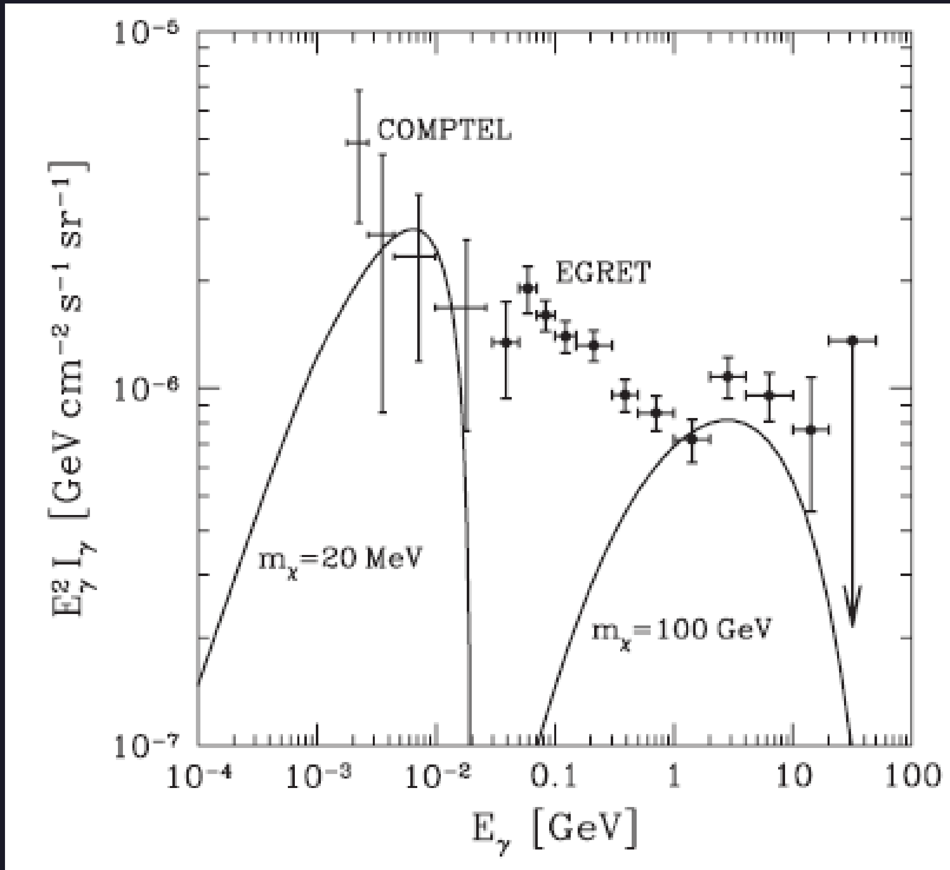
✓ The method is complementary to the traditional one

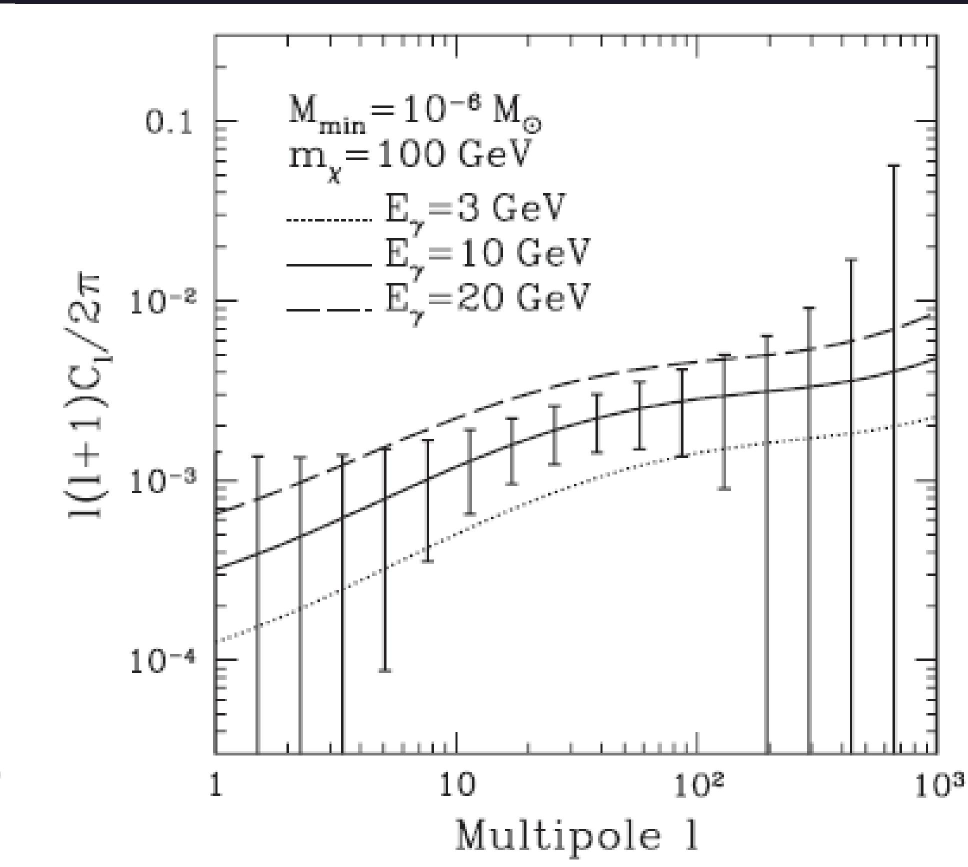
$$I_{tot}(E,b,l)=A+B\, I_{Gal}(E,b,l)$$

✓ Not Peculiar of DM, yet a bound or detection would constrain DM properties



Intrinsic extragalactic anisotropy





"dark matter annihilation also produces a characteristic anisotropy of the CGB, which provides a powerful tool for testing the origin. [...] As the intensity of photons from annihilation is proportional to the density squared, we show that the predicted shape of the angular power spectrum of gamma rays from dark matter annihilation is different from that due to other astrophysical sources such as blazars."

S. Ando & E. Komatsu PRD73 023521 (2006) [astro-ph/0512217]

Anisotropy at high energy

However, the signature depends on several parameters (Energy spectrum, minimum DM clump mass, cosmological evolution,…). Cosmic variance also prevents to measure the lowest multipoles!

$$F(E_{\rm cut},\hat{n}) \propto \int_0^\infty {\rm d}z\, \frac{\rho^\alpha(z,\hat{n})}{H(z)\,(1+z)^3} W(E_{\rm cut},z)$$

Cumulative photon flux

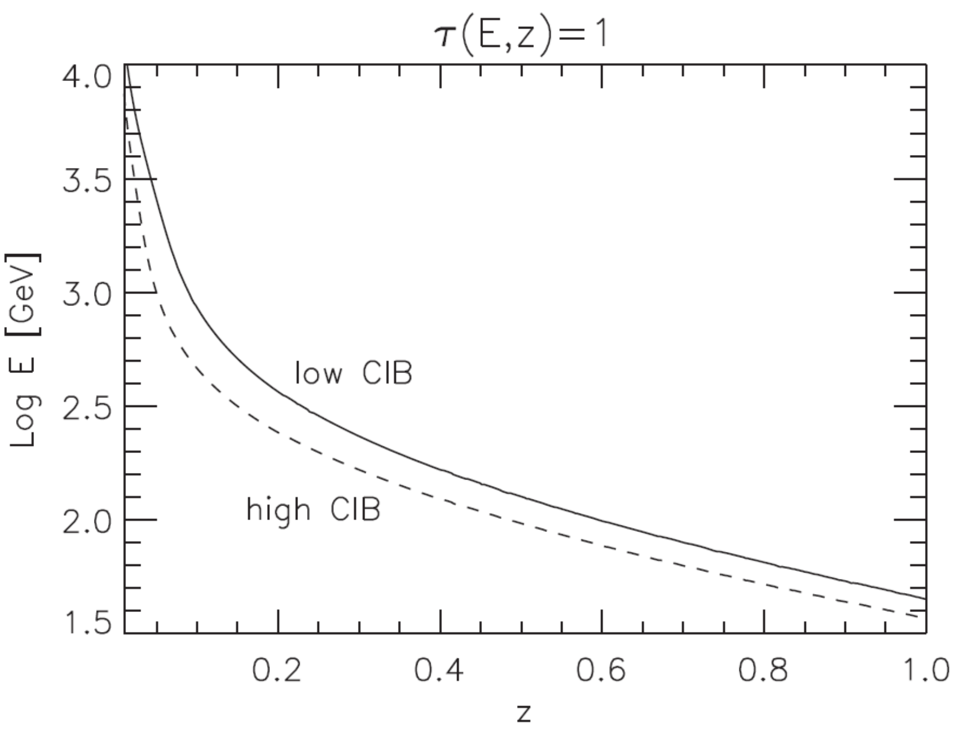
$$W(E_{\rm cut},z) \equiv \int_{E_{\rm cut}}^\infty {\rm d}E\, g[E(1+z)]\, e^{-\tau(E_\gamma,z)}$$

Window function

✓ When the horizon is at z<< 1, the signal mostly depends on α (modulo τ)

✓ Lower statistics, but more robust predictions: look at E>0.1-1 TeV!

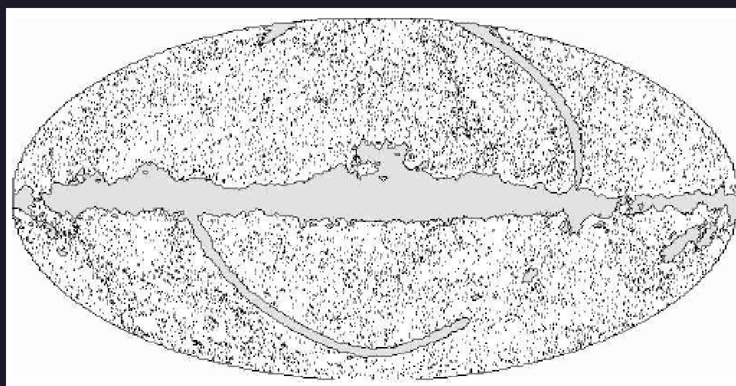
A.Cuoco, S.Hannestad, T. Haugbolle, G. Miele, PS & H. Tu, astro-ph/0612559



Other interesting features

✓ Especially at large scales, the near structures are responsible for the anisotropy pattern.

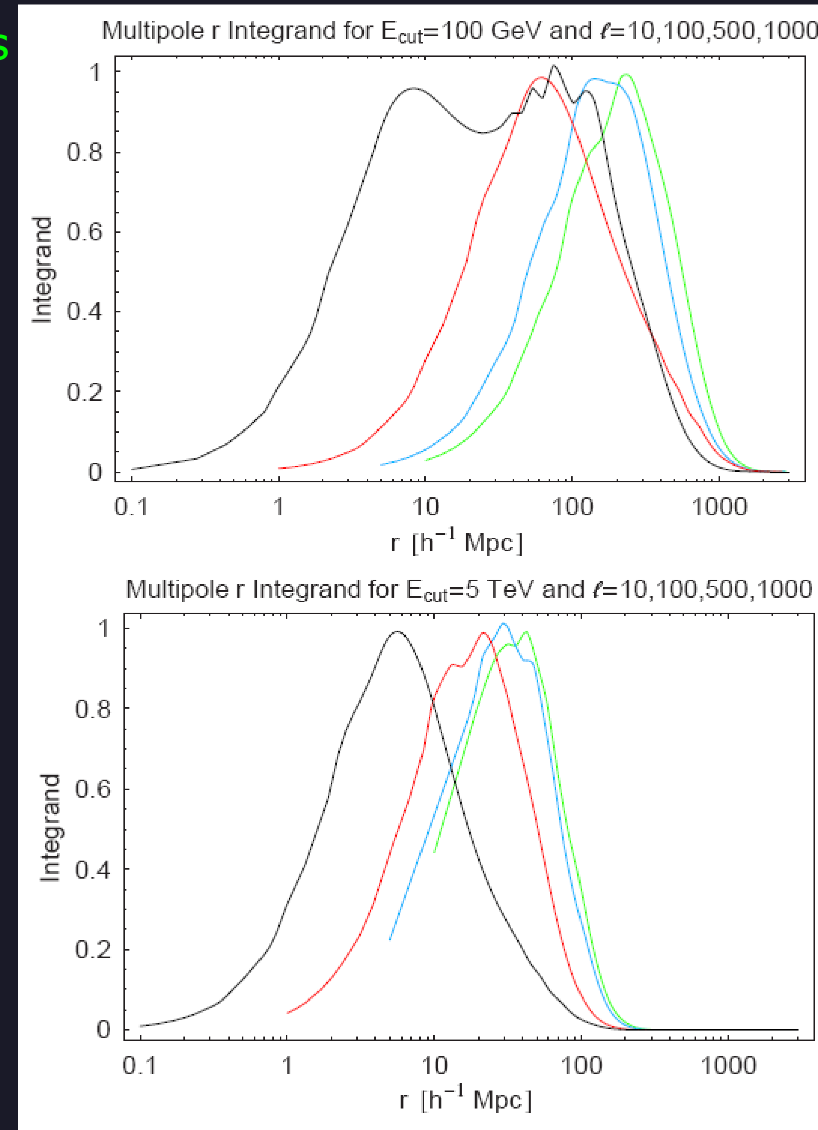
✓A “real” LSS catalogue can be used for predictions



- ➢ more modes (a_{lm} *vs.* C_l)
- ➢ no cosmic variance limitation

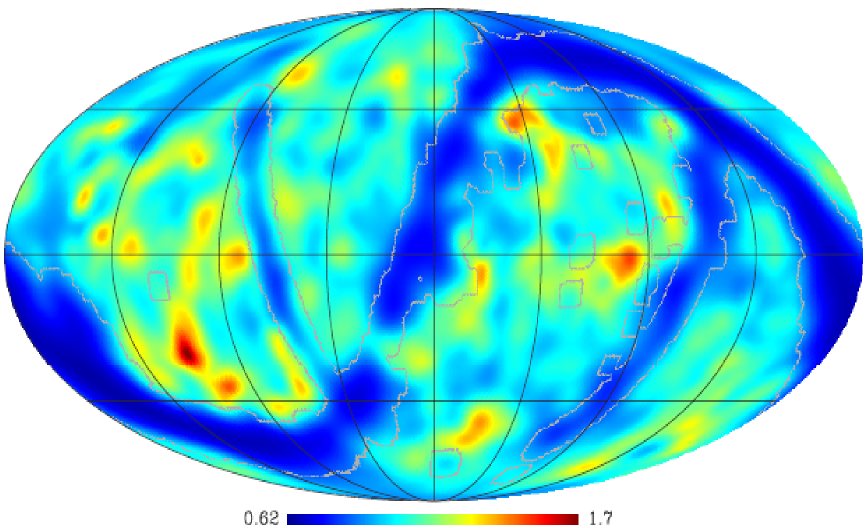
✓ The relative anisotropy is higher the higher the energy cut. This compensates to some extent the problem of the lower statistics available

$$a_{lm} \sim \frac{\Delta I_{lm}}{\langle I \rangle}$$

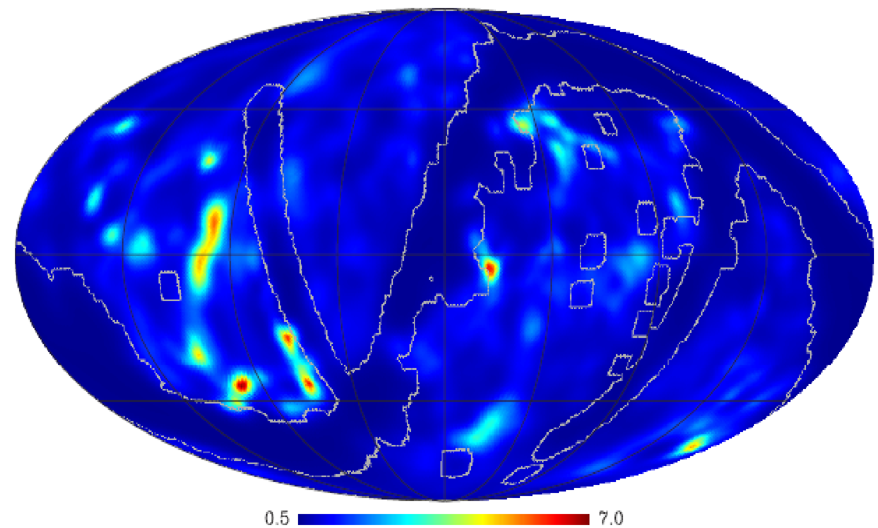


Sky Maps

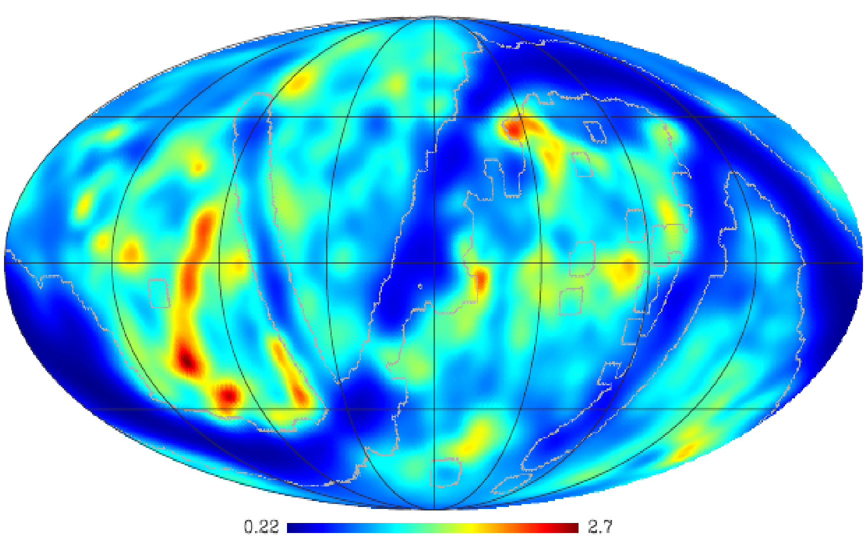
100GeV flux for linear density correlation



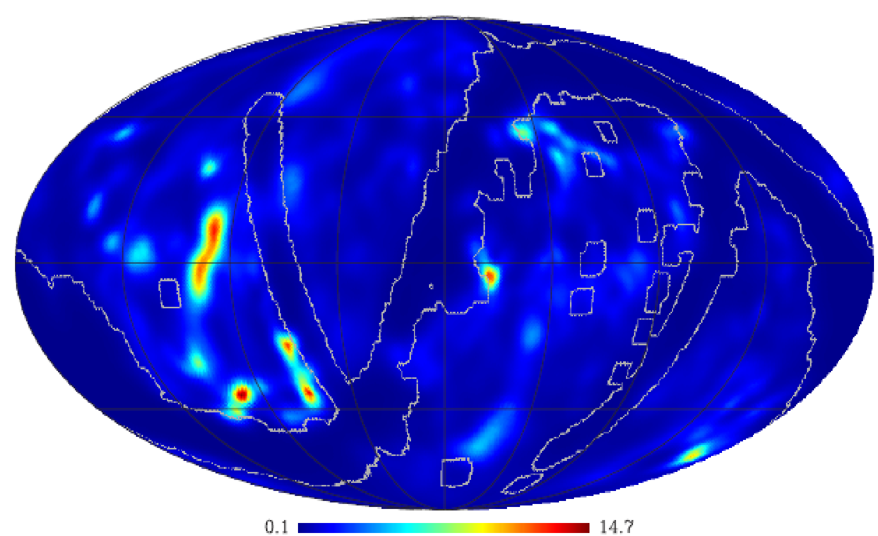
100GeV flux for squared density correlation



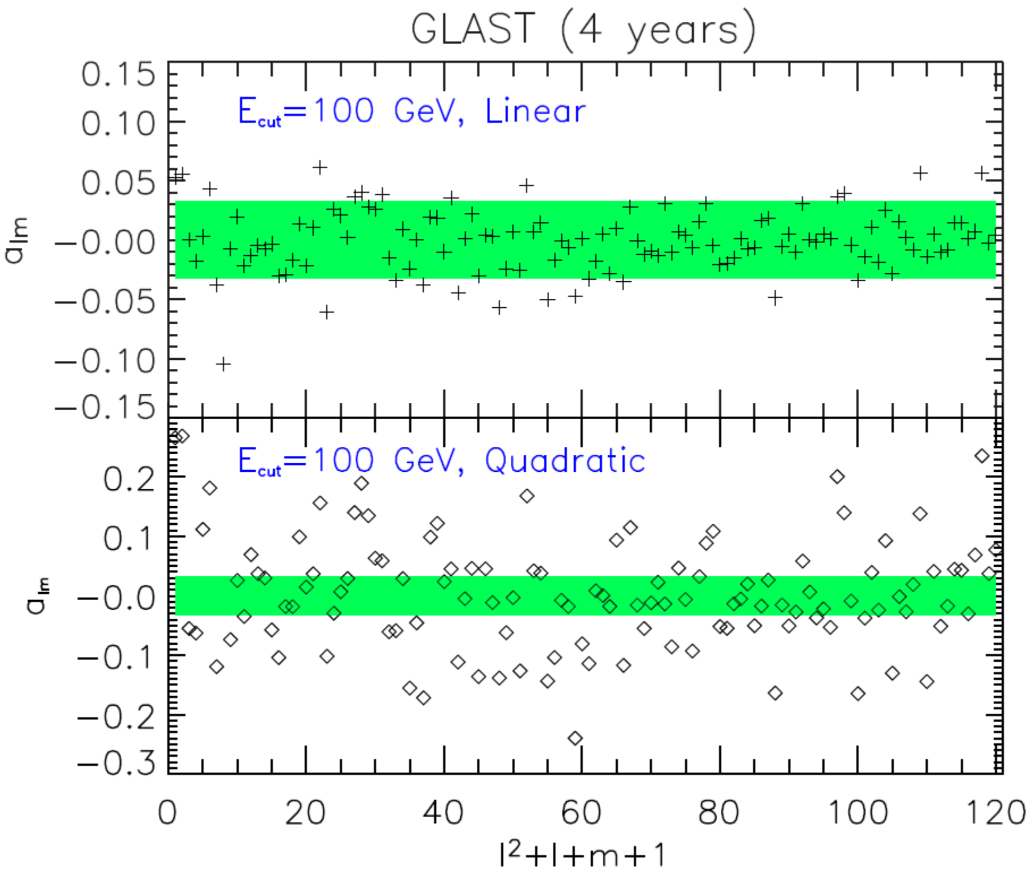
1TeV flux for linear density correlation

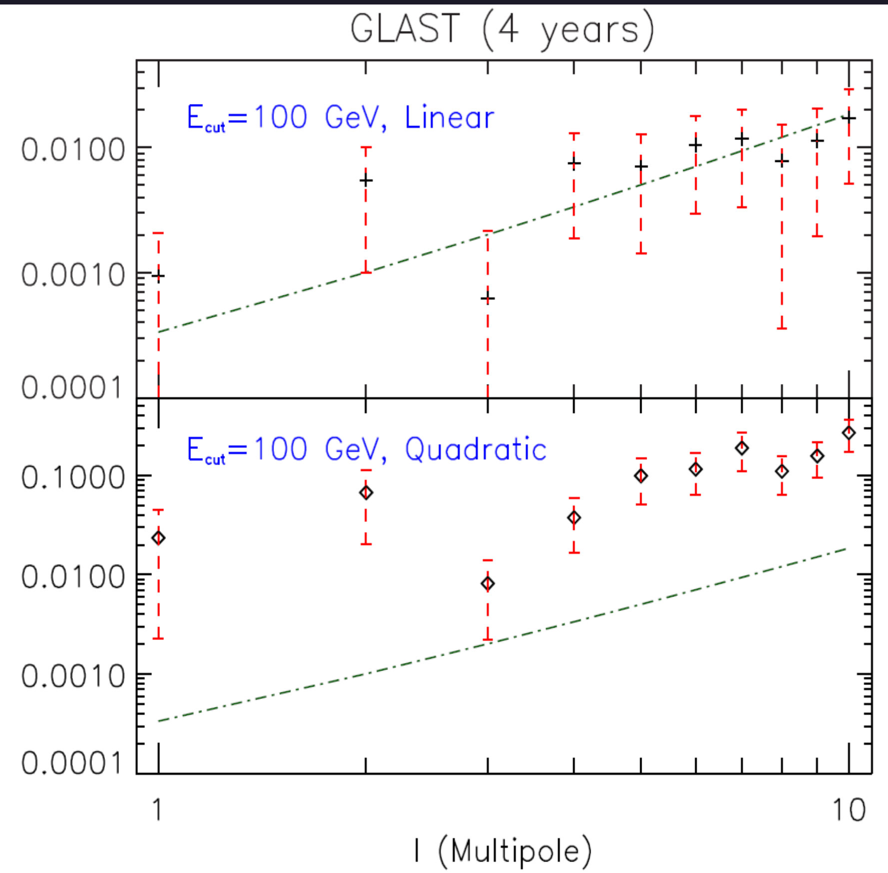


1TeV flux for squared density correlation



Expectations for GLAST

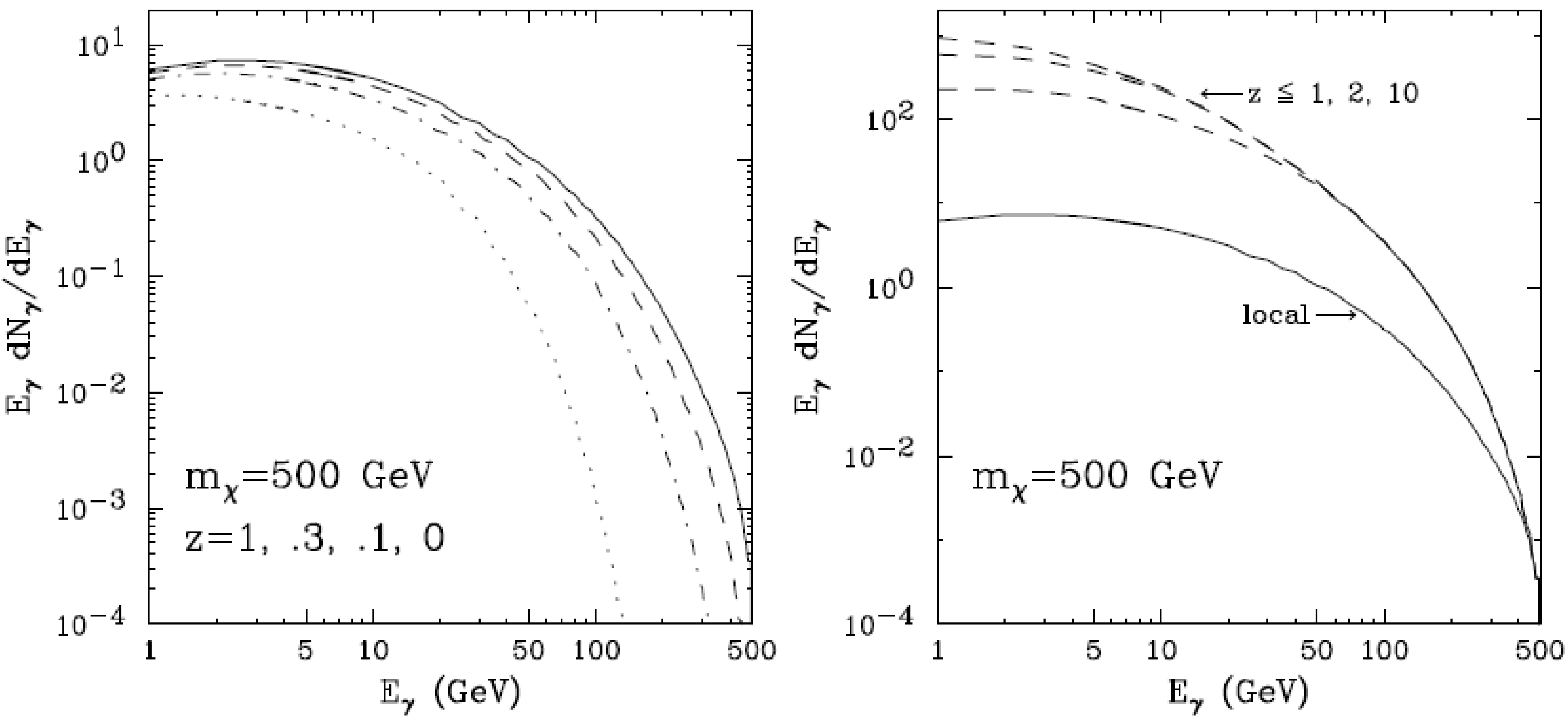




$$F_{10}(E_{\rm cut}, \hat{n}) = \sum_{lm}^{l_{\rm max}=10} a_{lm} Y_{lm}(\hat{n}) \qquad \sigma_{a_{lm}}^2 = C_l^N = \frac{4\pi f_{\rm sky}}{N_\gamma}\left(1 + \frac{N_{\rm CR}}{N_\gamma}\right)$$

$$N_\gamma = t \cdot g_{\rm cut} \cdot DC \cdot \Omega_{\rm fov} \cdot f_{\rm m} \cdot \int_{E_\gamma}^{\infty} {\rm d}E\, A_{\rm eff}(E) I_\gamma(E)$$

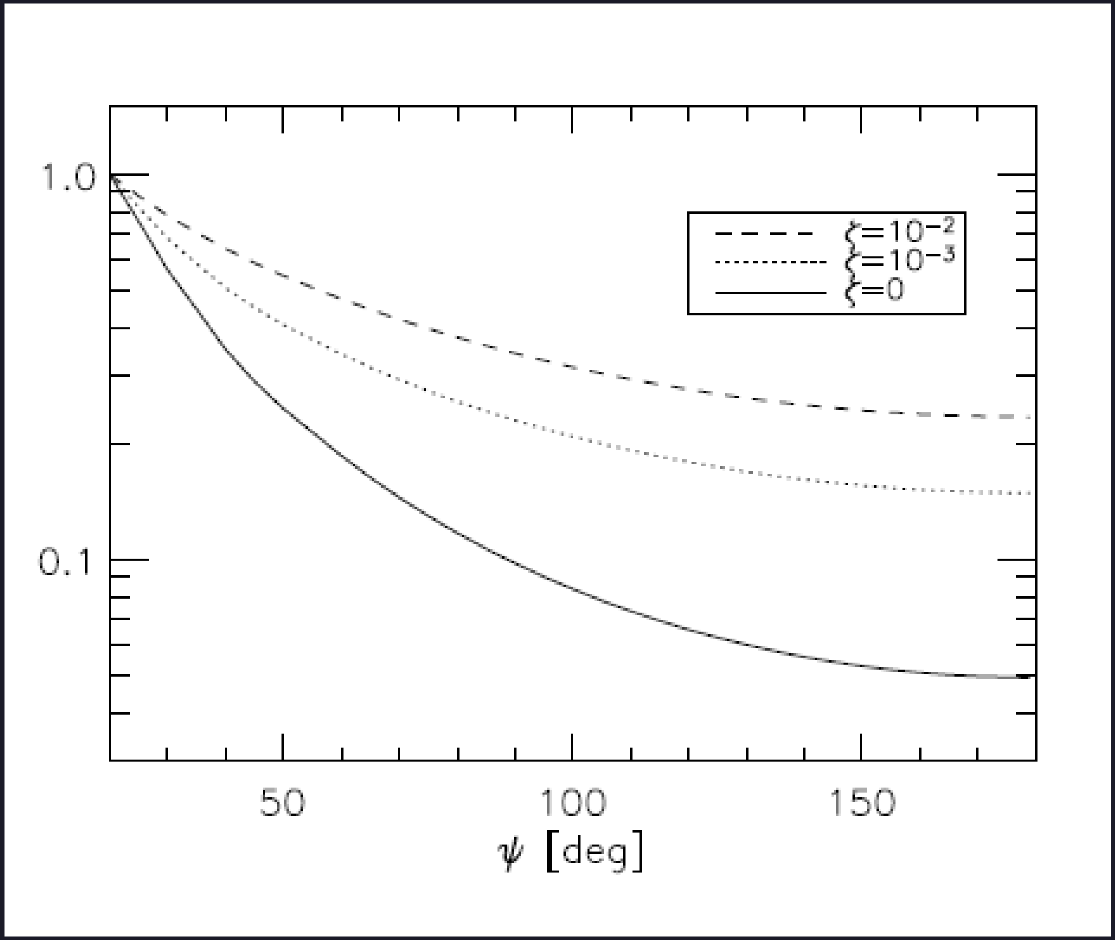
Signatures in the Energy Spectrum



D.Hooper and PS, astro-ph/0702328

Galactic dominance Signatures

Offset position in the halo



Cylindrical symmetry in the limit of spherical halo; O(10%) asphericity expected, yet the symmetry axes of the ellipsoid are unknown

Compton-Getting effect

- ✓ The baryonic disk of the Galaxy is suppported against radial collapse by its angular momentum

- ✓ The dark halo is supported by random velocity (a collisionless pressure)

- ✓ The disk rotates into the rest frame of the DM halo with velocity u=220 km/s. A CG dipole with amplitude of about 0.3% is expected if DM dominates the diffuse flux

- ✓ Note that this is a DM-peculiar effect, since astrophysical contamination from the disk would be co-rotating with us, at better than 10%

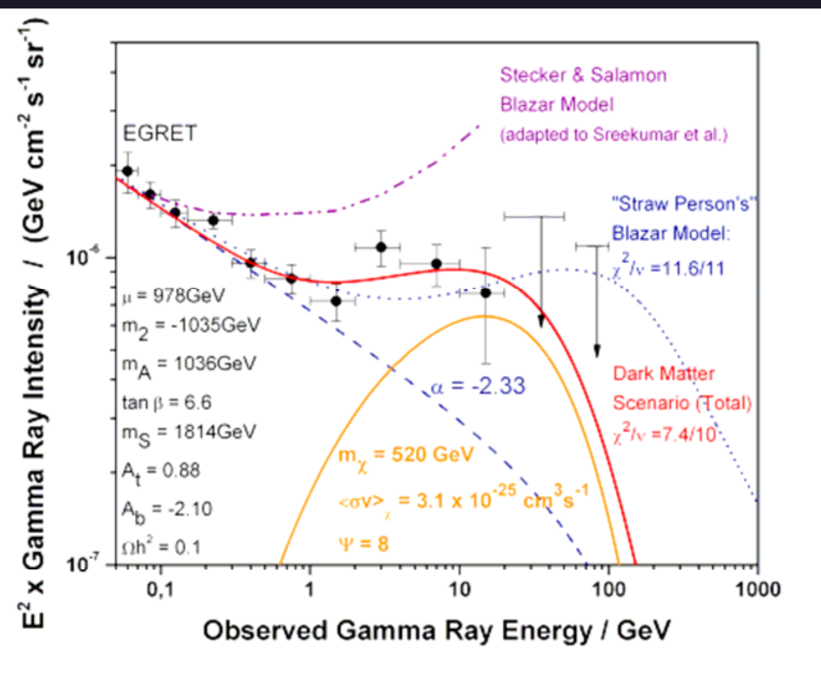
D.Hooper and PS, astro-ph/0702328

Prospects for Detection

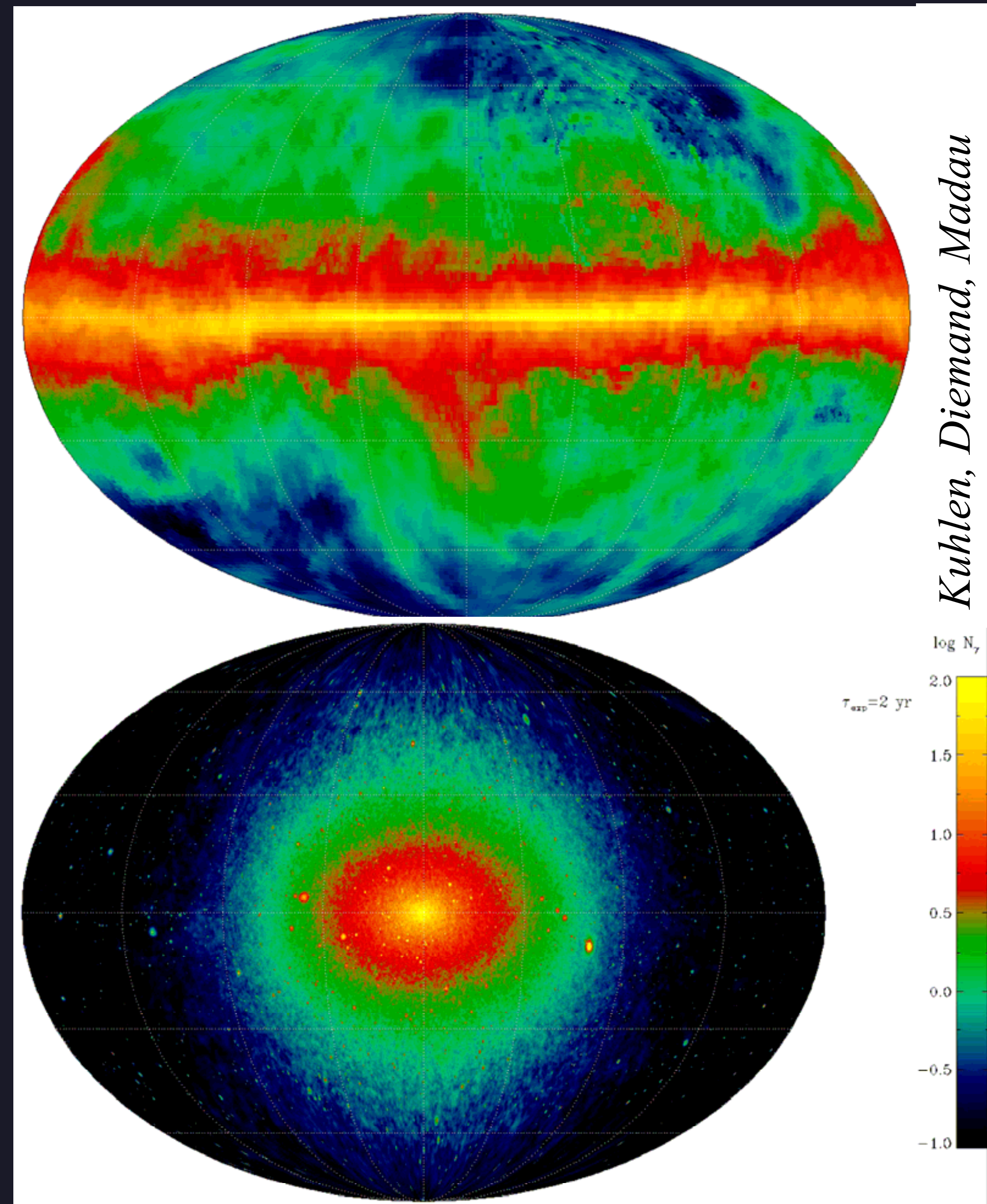
Prospects for Detection - I

✓Astrophysical & DM signals have different angular shapes

✓Energy spectra very different

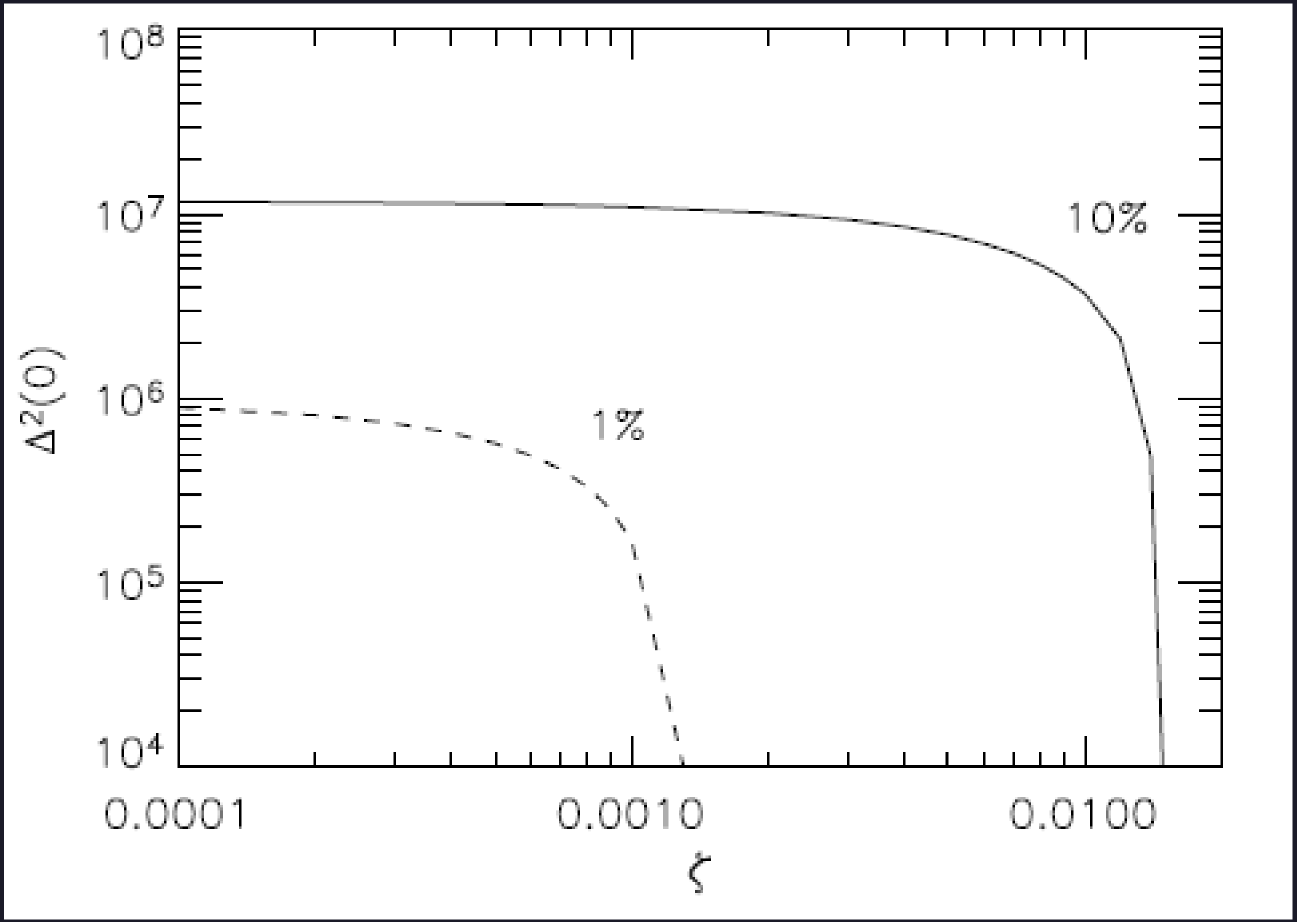


✓How large must the DM contribution be to be interesting?



Kuhlen, Diemand, Madau

Prospects for Detection - II



$<\sigma_{ann}v>$=3 x 10^{-26} cm^3 s^{-1} m_χ= *100 GeV*

Concluding Remarks

Conclusions

- Unveiling the nature of DM is one of the greatest unresolved mysteries of astrophysics and cosmology, and one of the few arguments in favor of physics beyond the standard model

- In most models, DM may be detectable in one or more ways (direct, indirect or collider searches). One promising way is via the gamma rays produced via DM annihilation

- Many candidate sources exist in the Universe. Diffuse fluxes, besides spectral features, have peculiar angular shapes. The large scale ones are robust and deterministic. If the emission is at least at the few percent of the overall diffuse flux, there are good chances of DM detection.

- Small-scale structures encode important statistical information, but extremely model-dependent. In the future, if we are lucky enough we may use gamma-maps to extract information on the clustering properties of matter on relatively small scales

This field requires combined efforts of particle physicists (theoreticians & accelerator experimentalists), simulation experts, cosmologists, underground lab physicists, astronomers, ν & γ astroparticle physicists…

If you still think it is not worth studying DM…

Remember: the dark side rules the universe!